The Emergence of Active Perception – Seeking Conceptual Foundations

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Declaration

I declare that this thesis has been composed by myself and that the research reported here has been conducted by myself unless otherwise indicated.

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Abstract

The aim of this thesis is to explain the emergence of active perception. It takes an interdisciplinary approach, by providing the necessary conceptual foundations for active perception research – the key notions that bridge the conceptual gaps remaining in understanding emergent behaviours of active perception in the context of robotic implementations. On the one hand, the autonomous agent approach to mobile robotics claims that perception is active. On the other hand, while explanations of emergence have been extensively pursued in Artificial Life, these explanations have not yet successfully accounted for active perception.

The main question dealt with in this thesis is how active perception systems, as behaviour-based autonomous systems, are capable of providing relatively optimal perceptual guidance in response to environmental challenges, which are somewhat unpredictable. The answer is: task-level emergence on grounds of complicatedly combined computational strategies, but this notion needs further explanation.

To study the computational strategies undertaken in active perception research, the thesis surveys twelve implementations. On the basis of the surveyed implementations, discussions in this thesis show that the perceptual task executed in support of bodily actions does not arise from the intentionality of a homunculus, but is identified automatically on the basis of the **dynamic small modules** of particular robotic architectures. The identified tasks are accomplished by **quasi-functional modules** and **quasi-action modules**, which maintain transformations of perceptual inputs, compute critical variables, and provide **guidance** of sensory-motor movements to the most relevant positions for fetching further needed information. Given the nature of these modules, active perception emerges in a different fashion from the global behaviour seen in other autonomous agent research.

The quasi-functional modules and quasi-action modules cooperate by estimating the **internal cohesion** of various sources of information in support of the envisaged task. Specifically, such modules basically reflect various computational facilities for a species to single out the most important characteristics of its *ecological niche.* These facilities help to achieve internal cohesion, by maintaining a *stepwise evaluation* over the previously computed information, the required task, and the most relevant features presented in the environment.

Apart from the above exposition of active perception, the process of task-level emergence is understood with certain principles extracted from four models of life origin. First, the fundamental structure of active perception is identified as the stepwise computation. Second, stepwise computation is promoted from baseline to elaborate patterns, i.e. from a simple system to a **combinatory system**. Third, a core requirement for all stepwise computational processes is the comparison between collected and needed information in order to *insure* the contribution to the required task. Interestingly, this point indicates that active perception has an inherent pragmatist dimension.

The understanding of emergence in the present thesis goes beyond the distinction between external processes and internal representations, which some current philosophers argue is required to explain emergence. The additional factors are *links* of various knowledge sources, in which the role of conceptual foundations is two-fold. On the one hand, those conceptual foundations elucidate how various knowledge sources can be linked. On the other, they make possible an interdisciplinary view of emergence. Given this two-fold role, this thesis shows the unity of task-level emergence. Thus, the thesis demonstrates a cooperation between science and philosophy for the purpose of understanding the integrity of emergent cognitive phenomena.

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Part I

Preliminaries

Chapter 1

Introduction

1.1 Aim of the Thesis

The aim of this thesis is to explain the emergence of active perception, by focusing on the processes of emergence at the task level, as seen in present research on active perception, which is a branch of research on behaviour-based systems. The envisaged emergence is explained from a multiplist point of view – explanatory interlock – which is realised in the establishment of a variety of conceptual foundations.

There are two aspects to an informative theory of active perception – scientific understanding and philosophical explanation. On the scientific side, the present thesis emphasises the need for an explanation of *how* active perception systems accomplish their tasks. In particular, two important properties of active perception have not been identified in previous discussions of the topic. One is the understanding that active perception systems accomplish their tasks through emergence, as opposed to full determination by design. The other is that the course of emergence mostly takes place at task level, i.e. during run-time (as opposed to learning), in support of the accomplishment of certain tasks. Specifically, the emergent processes at the task level of active perception implicitly head toward the accomplishment of tasks without being fully pre-determined in the design of active perception systems/implementations.

On the philosophical side, this thesis raises the need to go beyond the distinction between *internal* and *external* processes of emergence, which relate to the determinative powers of internal representations and organism-environment interactions respectively. Those processes are currently the focus of philosophical discussions on the emergence brought forth by behaviour-based systems. The problem is that attributing determinative power to different sources relative to skin and skull does not seem efficacious in explaining *why* active perception systems in general can accomplish their tasks in the course of emergence. Hence, as yet, the explanation of the envisaged task-level emergence remains incomplete.

As an alternative to the above distinction, discussions in the present thesis concentrate on developing an explanation of emergence by answering the *why* question – why active perception systems in general can accomplish their tasks in the course of emergence. This why question is to be answered by explaining task-level emergence using a combination of theoretical constructs and philosophical notions, in the hope of explaining the unity of emergent processes without sacrificing the comprehensive coverage over the related strategies of implementation.

To address the above *how* and *why* questions, the present thesis introduces a notion – activeness – which concerns *what* makes active perception work. As a consequence, the efforts to build conceptual foundations can be seen as contributing to an understanding of activeness.

1.2 Background Knowledge

1.2.1 Definition and Analysis of Active Perception

The term 'emergence of active perception', in the present thesis, is meant to denote the emergence of perceptual facilities for bodily actions which is maintained by the active processes of perception. The active processes of perception, according to current research in active perception, comprise (1) sensory-motor activities (such as saccades and pursuit) or bodily movements which contribute to perceptual tasks by focusing iteratively on the most relevant perceptual inputs in the environment, and thereby contribute to simplifying perceptual judgements, (2) perceptual processes that fulfil perceptual tasks not simply by building up perceptual features for recognition (as seen in Marrian visual systems[1]) but instead by providing guidance for, and consequently contributing to, bodily actions. In other words, active perception is deemed to be *active* on the grounds of (i_a) the orientation toward most *relevant* inputs which is maintained by sensory-motor activities, (i_b) the *simplification* of perceptual processing made by bodily actions, (i_c) iterative arrangement along with the changing environment, and (ii) the *use* of perceptual judgements *only* for the need of bodily actions, i.e. perceptual processes must be task-specific.

It is worth noting that the selection of *internal* processes may contribute to active perception, but there must be some internal processes subserving the control of sensory-motor or bodily actions in the first place, as required above by ($\mathrm{i}_{a,b}$). Specifically, the above points (i_a) and (i_b) concern selection of perceptual *processes* that in turn serve to select the sensory-motor or bodily *actions* that direct the perceptual system toward most (relatively, as the systems can respond) relevant perceptual information in the environment. Internal processes, as a requirement of active perception, serve not only to drive sensory-motor and bodily actions, but also to work out what perceptual information (to be collected) is most relevant to the required tasks. Accordingly, active perception systems are active because they carry out process selection for computing the most relevant perceptual information (to the required tasks) *and* thereby direct their receptors/sensory organs toward certain perceptual information in the environment. In other words, active perception systems manage to *participate* with the environment interactively in order to collect the needed information for required tasks.

The requirement (i_c) is the *iterative* arrangement along with the changing environment. This serves to complement the previous requirements ($\mathrm{i}_{a,b}$), by further stipulating that these two requirements must be maintained in iterative steps, so that observers can take account of environmental changes and thereby hopefully tend to be more likely to *keep* track of the changing environment. As

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[1] Marrian visual systems are initiated by David Marr (1982).

a further but optional constraint, an active perception system may carry out its iterative process arrangement incrementally, as manifested in the attentive control of saccadic movements. The incremental processes of information collection make possible the influencing of later steps by previous results.

Requirement (ii) concerns the economy of internal processes, which certainly has an effect on the economy of external (sensory-motor and bodily) actions. The emphasis of (ii) is that internal processes must be highly task-specific, as opposed to serving general-purpose functionality. In particular, there must be certain *heuristics* for driving sensory organs *or* deriving perceptual features, in order to provide efficient perceptual guidance of bodily actions – the tasks. As an example, making a decision under uncertainty is facilitated by certain task-specific heuristics which manage to make a quick judgement over the relating tasks, by deriving the most likely perceptual features and ignoring details.

Note that the conception of active perception does not consist of a single criterion, but comprises *a combination of requirements*, as discussed above. It is not hard to realise that different research paradigms of active perception may adopt different combinations of requirements. It is even possible that different organisms need different conceptions of active perception.

A confusion concerning the *conception* of active perception may arise, namely that the successful performance in the real environment (which is subject to real-time constraint) is the ultimate criterion of active perception. This confusion should be avoided. While it serves to *motivate* the present paradigm of active perception research, the success in real-time performance is not required in the *definition* as a characteristic of active perception. Rather, real-time performance is an envisaged *result* of implementation. By conception, it is possible that active perception systems turn out respond unsatisfactorily in the real environment (probably due to unstableness or the time-consuming computation for fulfilling requirements $\mathrm{i}_{a,b,c}$). However, in reality, active perception systems actually perform satisfactorily in the real environment. It needs *explanation* as to why such systems, as characterised in the aforementioned definition, turn out to be so competent.

1.2.2 The Relation of Active Perception Research to Traditional AI.

Active perception research stands as a reaction against Marrian vision theory and its generalisation to other perceptual modalities. Note that Marrian vision theory is a hallmark of traditional AI. As a direct consequence, the *movement* of perceptual systems arises as a requirement of active perception systems in order to select perceptual inputs by participating in the environment, as manifested in requirements ($\mathrm{i}_{a,b,c}$) of active perception. Apart from this difference from traditional AI, active perception research departs from traditional AI in two regards. Firstly, traditional AI adopts general-purpose programs (as opposed to *task-specific facilities*) which attempt to take full account of the environment by reconstructing a fully elaborate map. Secondly, active perception research is a reaction to model-based systems, by shifting to *behaviour-based robots*, which are also termed *autonomous agents*.

Task-specific Facilities. Consider the first departure – undertaking task-specific facilities in active perception systems. This is requirement (ii) of active perception. Provided that this requirement is fulfilled, together with the requirements ($\mathrm{i}_{a,b,c}$), a perceptual system which completely consists of a model of symbolic descriptions can be *conceived* of as an active perception system. Given this, active perception research is not entirely abstinent of symbolic descriptions. There are indeed continuities between traditional AI and active perception research (Brooks 1992b). Those continuities would not prevent a perceptual system from being active, because in the previous requirements on active perception (($\mathrm{i}_{a,b,c}$) and (ii)) there is no mention of the adoption of symbolic descriptions. So long as the implementation is successfully working in a *real* environment – the original motivation for active perception research – the architecture of this implementation will contribute to the understanding of active perception. Yet, this is a real departure from traditional AI, because the adopted symbolic descriptions no longer serve to expand or elaborate a *full* model of the world. Conversely, the robot design of active perception systems emphasises *task-specific* heuristics/utilities.

Behaviour-based Systems. Consider the second departure from traditional AI. Although a perceptual system based on task-specific *descriptions* can be conceived of as active, merely being labelled 'active' does not guarantee its successful implementation in the real environment. In fact, the present implementations of active perception are rarely grounded on such descriptions. Rather, active perception research is mostly *behaviour*-based. Although this may be regarded as simply a contingent fact of academic research – that active perception research arises as a branch of mobile robotics – this fact seems to have a theoretical ground. To wit, it is generally a difficulty with mobile robotics to expect successful implementation from using pre-specified models of the unpredictable environment. This difficulty seems to be a central motivation for behaviour-based robotics. This approach is successful in implementing low level cognitive functionality, such as the navigation implemented in Brookian robotics – an approach to robotics which emphasises the *embodied* and *embedded* activities for the implementation of *situated* robots (see discussions in chapter two).

The task-specific facilities implemented in the behaviour-based approach are different from those in traditional AI, mainly because the behaviour-based task-specific constraints are more fine-grained and their response to environmental conditions is rapidly incremental. This is a design strategy of behaviour-based control (Mataric 1993).

With this strategy, a behaviour-based system is constrained by small and incremental movements which rapidly adapt to current environmental circumstances. The way to accomplish tasks is not entirely characterised by pre-fixed categories (e.g. knowledge representations), unlike the planning for accomplishing the tasks in traditional AI.

Basic Strategies of Implementation Underlying Behaviour-based Systems. Behaviour-based systems can be largely characterised according to their basic strategies of implementation, as seen below.

Situatedness and Embodiment. The above-mentioned capability of behaviour-based systems to rapidly adapt to current environmental circumstances is grounded on two characteristics of such systems – situatedness and embodiment (see detailed discussions in chapter 2). Both characteristics uphold the importance of direct contact with the environment, as opposed to maintaining searching on the knowledge representations of a world model. However, these two characteristics have respective emphases. In brief, the notion of situatedness concerns organisms' relation to the environment, while the notion of embodiment concerns the effects brought about on account of organisms' bodies.

Being situated, behaviour-based systems count on rapid contact with the various aspects of the environment without undergoing a long path of search over a world model. The gist is to let organisms intensively contact various aspects of the environment, i.e. letting organisms confronting with and wandering between various situations. As Brooks describes, such systems *continuously refer to* sensors rather than maintain *searching* in the internal model. Information from sensors is, and must be, responded to 'in a very short time span' (Brooks 1991b, italics added).

Being embodied, a behaviour-based system gathers information based on various *effects* of its *body* which are evoked when the system contacts the environment: including the sensory features provided by their sensors, the movements of their bodies, and even the new relations with the world created by their bodily actuators or posited by their sensory-motor actuators. In this regard, Brooks contends that in order to gain precise understandings of the world, '[a]ll the details and issues of being in the world must be faced' (ibid., p. 15).

An important effect of the aforementioned direct contact with the world, as Brooks contends, is the physical grounding of the *processing* going on within a computational system. However, Brooks does not discuss the hybrid cases where embodied systems are endowed with knowledge representations, hence, he does not really explain *symbol* grounding. Despite this, it is fair to say that Brooks brings a new light to resolving the symbol grounding problem. To wit, because of the direct contact with the world, there is no need for a computational system to rely *completely* on knowledge abstraction. In this particular regard, it is not unfair to say that the capabilities of behaviour-based systems go beyond traditional AI.

Accomplishing Tasks Based on a Collection of Modules. The accomplishment of tasks in the behaviour-based approach takes advantage of the convergent effects of various modules distributed throughout the behaviour-based system without any central control. Tasks can still be decomposed, on the basis of various task-specific constraints. However, task-specific decomposition is maintained, as Mataric (1993) describes, in a way very different from intuitive software engineering. The convergent effects are not maintained through the correctness and consistency of information exchanged between modules, but through the mediation of the *world* and the *current* states and goals of the robot/system (ibid.). Because of the indispensable unpredictability brought about in the above course of mediation(see relating discussions in Section 2.3, page 34), these two sources of determination – world and current system conditions – are by no means entirely pre-categorised. and consequently this determination of behaviour is very different from the maintenance of task-specific computation in traditional AI.

The current states and goals are maintained by a variety of modules, depending on the tasks and the environment, as we will see when we examine in detail the architectures of active perception systems. However, modules in a behaviour-based system must be small, as Mataric (1993) contends. This is because the control of a behaviour-based system is distributed, which may result in high complexity unless the inter-module dependence and computation is minimised.

Emergence on Grounds of Situated Robotics. A fascinating property of the active perception systems, which are principally behaviour-based as just mentioned, is their *emergent* functionality. The situated activities of robots provide abundant emergent phenomena because the generated capabilities are basically global behaviours arising from local activities. More intriguingly, the emergence takes place at the *task* level, as opposed to evolutionary, developmental or learning levels. That is, the perceptual *information* provided by active perception systems, in contrast to the generated *capabilities* resulting from computer learning, is itself an emergent phenomenon. The task-level emergence is a distinguishing property that makes active perception research outstanding in the understanding of emergence, because it is as yet the only case of emergence happening at the *task* level. The present thesis is dedicated to the study of emergence at this level, in order to contribute to the study of emergence.

1.3 Seeking Conceptual Foundations

1.3.1 The Explanatory Role of Conceptual Foundations

The term 'conceptual foundations' is meant in this thesis to signify the key notions that bridge the conceptual gaps remaining in understanding emergent behaviours of active perception in the context of robotic implementations. The emphasis is on the conceptual explanations required, as opposed to conceptual analysis of terminological usage, philosophical notions, theoretical comparison, numerical description, computer implementation, or experiment.

Like most philosophical notions, conceptual foundations are presented at the level of concepts; yet these activities, despite being conceptual, are distinct. Conceptual foundations can be seen as a middle ground between philosophical notions and theoretical constructs. The idea of this thesis to develop conceptual foundations is inspired by a distinction made by Patee (1995) in the context of ALife – between genes and biological principles (including dynamical systems theory) – for explaining different roles in the determination of life. As Patee points out, genes provide *information* while biological principles (including dynamical systems theory) serve as *physical principles.*

Although Patee labels the distinction he has drawn as 'epistemological', it seems more appropriate to see the above two explanatory roles as the conceptual foundations of the issue which concerns Patee – the different roles played by genes and biological principles in the determination of life. The reason is two-fold. On the one hand, the above distinction does not seem to fall squarely into the categories of traditional epistemology, which concerns *general* properties of knowledge and its justification, specifically comprising the scope and limits of knowledge, its sources and justification, and sceptical arguments over claims of knowledge (Grayling 1996). On the other, the aforementioned notion raised by Patee – genes providing information vs. dynamical systems theory characterising physical principles – serves as conceptual groundwork to enable discussion of an issue arising from the exposition of scientific theories. Such a notion can consequently be considered as a conceptual foundation.

1.3.2 Epistemology cf. Conceptual Foundations.

The provision of conceptual foundations can be regarded as a particular aim of epistemology. That is, certain epistemological discussions aim to establish the conceptual foundations of a certain field. Hence, there is a typical difference between epistemology and conceptual foundations: conceptual foundations, by necessity, are intrinsically associated with a *particular* field of academic knowledge. By contrast, epistemological discussions may be focused on a *general* notion for explanation, e.g. representation or emergence.

Unlike epistemology, conceptual foundations emphasise contrasts in explanatory stances. For example, regarding the control of bodily actions, different explanatory stances may be highlighted, say between externalism and cognitivism, and accordingly either organism-environment interaction or the information processing in the brain is defended. Epistemological discussions emphasise more the defence or criticism of such explanatory stances *in general.* Different stances are compared, usually in paired opposites, and a certain stance is seen as more plausible than others. The supporting evidence may be collected across fields. By contrast, conceptual foundations emphasise the explanation of *particular phenomena* in a specific field, e.g. in the field of cognitive development, or alternatively in active perception. Evidence in a certain field will be collected to support one *or even some* explanatory stances, depending on which particular phenomena are to be explained. For example, emergence can be explained by a hybrid of explanatory stances, such as the combination of exploration and exploitation.

The fact that more than one stance of explanation may be simultaneously appropriate can result from a contrast: a common term (emergence) being applied to a variety of (emergent) phenomena which are subject to different mechanisms. In this regard, the work on conceptual foundations seems to be more flexible than epistemological discussion, in focusing on different phenomena and consequently accepting critically a variety of explanatory stances.

An advantage of developing conceptual foundations, beyond the scope of traditional epistemological discussions, is to extract from the scientific experiments or computer implementations of a certain subject matter (e.g. active perception, or embryogenesis) their latent explanatory thrusts which may contribute to the theoretical understanding or philosophical deliberations in connection to that subject matter. For example, the algorithms in Brooksian robotics are conceptually elaborated in support of externalism (see detailed discussions in chapter 7), a philosophical thesis which attributes cognitive capacities to organism-environment interactions. By contrast, the algorithms in traditional AI are generally taken to support cognitivism, another philosophical thesis which regards the search of a database as the prototype of cognitive behaviour. In addition, the notion of **factorial conditions** developed in the present thesis (see Section 5.4.1, page 176)[2] is a conceptual elaboration of certain strategies of implementation

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[2] Throughout this thesis, the number 'x' in the parentheses '(see Section x, page y)' refers to the section (or sub-section) where the addressed topic first appears in the present thesis. The number 'y' refers to the precise page where the given topic begins in that section. Notice that the topic in that section may continue across pages. In addition, when a term denoting a conceptual foundation (e.g. **factorial conditions**) first appears in the present thesis, it will be put in bold face (e.g. **factorial conditions**). Moreover, a conceptual foundation is necessarily a notion

undertaken in active perception research, such as Kalman filter, Snake, and the computation over certain specific variables in the implementation of Adept (a robot). This notion marks a difference between active perception systems and other behaviour-based systems, as we will see in chapters 5 to 7. Thus, the derivation of this conceptual foundation contributes to the theoretical understanding of active perception systems.

1.4 The Scope of the Present Thesis

As an interdisciplinary study this thesis has a broad scope. However, it has its emphasis – seeking conceptual foundations with which to explain the unity of emergent phenomena at the task level. With this emphasis, the present thesis does not plan to address everything relating to active perception research. In particular, this thesis does not aim to explain formally how the behaviour-based approach implements cognition or why this approach outperforms traditional AI, for the following reasons.

In implementing cognition, so far, it seems still difficult to provide a *formal* account which can explain the applicabilities of all behaviour-based systems, because the applicabilities of behaviour-based approach to *various* tasks and environmental conditions have not yet been fully examined, as Mataric (1993) indicates. As yet, only a limited range of possible robotic capabilities are implemented and examined. Note that a significant amount of *contingencies* confront the behaviour-based approach – that the architectures of behaviour-based systems are task-specific, that tasks are various, and that the computation remains dependent on the environment which is largely unpredictable. As a consequence, the range of implementations may be quite broad.

Given the remarks above, debates on the issues of whether and why the behaviour-based approach to intelligence generally outperforms traditional AI

(but not vice versa). Hence, for the sake of convenience the term 'the *conceptual foundation* of factorial conditions' is usually shortly written as 'the *notion* of factorial conditions'. Such a usage will apply to other conceptual foundations.

would be difficult to resolve on purely *formal* grounds. Comparison between these two paradigms needs not only to provide general explanations but also to consider explanations with respect to the aforementioned contingencies. Such a formal account is certainly worth pursuing someday, but it needs empirical supports from a broad range of implementations. The present thesis certainly cannot have so broad a coverage, but will instead focus on the explanation of a particular theme: the conceptual foundations for explaining the task-level emergence of active perception.

1.5 Outline of this Thesis

Chapter 2 presents the background to this research, including discussions of certain important notions, e.g. autonomy vs. adaptability, and underlying theories of behaviour-based systems, such as the subsumption architectures in Brooksian robotics.

Chapters 3 and 4 serve to analyse the present theories and implementations of active perception. Regarding the theories, discussions characterise the paradigm of active perception research by the distinction of the AB and the BC perspectives of active perception, which have certain commonalities but possess significantly different emphases. Regarding the implementations, the active perception systems discussed can be generally put into four groups, according to the difference between implemented capabilities. The first group concerns gaze control, including attentive control of saccades and the control of pursuit movements, to mention the two which are discussed most regularly. The second group consists of tracking systems, comprising Snake and dynamical Kalman filter (including Dickmanns' car). The third group has only one implementation, a distinctive type of active perception system – Adept – which deals with run-time planning of visual path. Its type of computation is also distinctive – the computation of certain critical variables which are characteristic of the geometric or geographic conditions relating to the envisaged visual path. The fourth group concerns active perception beyond the visual modality. Three implementations are discussed – Roberts' system of active haptic perception, Allen and Bajcsy's robot with visual-tactile integration, and Scheier and Lambrinos' robot with active categorisation. Cross-modal active perception is also illustrated, to convince readers of the following point: although understandings of active perception in current theories are mostly derived on the basis of systems of visual modality, active *perception* does include other modalities.

Efforts to build conceptual foundations are presented in chapters 5 and 6, which respectively address two dimensions of task-level emergence. Regarding the first dimension, chapter 5 serves to characterise the explorative and exploitative control of active perception systems in the form of conceptual foundations. Regarding the second dimension, chapter 6 strives to explain task-level emergence, specifically to account for why local activities lead to emergent phenomena – the accomplishment of required tasks.

In chapter 5, the analysis of active perception makes a distinction between **task identification** and **process arrangement**. The former concerns the appropriate initiation of processes, while the latter concerns the continuation of computation leading to the accomplishment of required tasks. In addition, argument suggests that the control of active perception systems consists of quasi-functional modules and quasi-action modules.

In chapter 6, task-level emergence of active perception is understood in terms of certain principles, which are generalised from four models of life origin – Rosen's (M,R)-system, Kauffman's autocatalytic network, Varela's notion of autopoietic unity, and Eigen's model of hypercycle. The understanding of task-level emergence is also based on a novel notion introduced in this thesis – **internal cohesion** – which particularly characterises the formation of serial orders in the task-level emergence of active perception.

The last section of chapter 6 provides a novel point of view to account for the relationship between environment, on the one hand, and the explorative and exploitative control of behaviour-based systems, on the other. This viewpoint is introduced in the notion of **inverse ecological niche**.

Chapter 7 seeks philosophical explanations over the task-level emergence of active perception. Discussions in this chapter show that the conceptual foundations which have been introduced can serve to elucidate the *unity* of emergent phenomena, which is conceived of in a Clark's notion: multiplist *interlock* of various aspects of cognition. The conceived interlock is realised by several links between knowledge sources, which are elucidated by the previously built conceptual foundations, mainly on grounds of the notion of internal cohesion, a notion serving to bring together all the detailed computational processes contributing to the generation of perceptual guidance in the course of task-level emergence. Thus, those conceptual foundations serve to explain the unity of task-level emergence.

Chapter 8 – the concluding chapter – draws together the conceptual foundations and philosophical notions discussed in the preceding chapters. Such conceptual foundations elucidate various links to merge different aspects of emergent phenomena in connection with active perception, with the effect that the unity of task-level emergence is explained. This chapter also suggests several directions for future research. With the establishment of those conceptual foundations and the above-mentioned unity, the thesis concludes that the derivation of conceptual foundations leads to a cooperation between science and philosophy for understanding the unity of emergent cognitive phenomena.

Chapter 2

Background Knowledge

This chapter fills in the background knowledge needed for understanding the task-level emergence of active perception. The background knowledge centres around three topics – organisms' adaptability to environmental factors, the internal control of behaviour-based systems, and the definitions of three regularly used terms.

The first topic divides in two – the relation of autonomy vs. adaptability (Section 2.1), and ecological niche (Section 2.2). Autonomy and adaptability are two sides of a trade-off relation, an account of which is crucial for understanding emergence. Ecological niche concerns the environment, with the emphasis on what organisms need for survival.

The second topic – the internal control of behaviour systems – concerns the root of active perception research in behaviour-based systems, including Brooks' subsumption architectures (Section 2.3), and the exploitative control of behaviour-based systems (Section 2.4). In particular, the present account of exploitative control is based on two implementations – Maes (1990b) and Steels (1990a) – their discussions of the appropriateness of internal control, and Thrun's (1992, 1995) account of active control. What they are generally concerned with is to go beyond the focus of Brooks' subsumption architectures in order to implement more complicated capabilities.

Regarding the third topic, the terms that need to be defined are: (i) internal representations, (ii) emergence, and (iii) certain considerations on the working definition of active perception, familiar from the introduction of this thesis. Internal representations are grouped into six types, according to different roles they play in the architectures of cognitive systems (Section 2.5). The term 'emergence' is defined as a negative counterpart of the concept of pre-determination, which in turn is defined in terms of pre-categorisation (Section 2.6). In addition, the previously defined term 'active perception' may be extended by further research. The present working definition, still, will be sufficient to engage with several aspects of active perception (Section 2.7).

2.1 Autonomy and Adaptability

2.1.1 Autonomy

The notion of autonomy mainly concerns the *self-sufficiency* of a certain (real or artificial) organism/system with respect to the deployment of one of its psychological traits and its generation from within the organism (in contrast to being imposed from the outside)[1] effectively.[2] In addition, the notion of autonomy also concerns the *fragility* of that trait, and the trait's underpinnings which are *non-controllable* from the external[3]. Note that the term 'self' does not necessarily refer to a *conscious* self, but instead refers to the *control* maintained by organisms' capacities/capabilities, which are often maintained unconsciously.

According to this notion of autonomy, a trait has high autonomy provided that the organism itself can deploy that trait with few instructions from the

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[1] The generation of capacities from within, as opposed to imposing instructions of behaviour on organisms from the outside, is a requirement of autonomy characterised by Boden (1995).

[2] For an autonomous organism, be it real or artificial, the supply of energy must suffice to maintain its activities, and its architectures should be designed so that irrecoverable deficit would not occur, as Pfeifer (1996) points out. The latter requirement concerns the fragility of that organism. We state this requirement explicitly.

[3] The requirement of non-controllability from the external is suggested by McFarland (1992). Also it is seen as an essential principle of animats (autonomous agents) by Pfeifer (1996), that agents must be 'function without human intervention, supervision, or instruction' (Pfeifer 1996, p. 5). Although environmental factors may *initiate* organismic internal functionality, the internal mechanism beyond simple stimuli-reaction association is itself non-controllable. No external factors can change the internal setting (or configuration). In this regard, Brooks' situated robots are *weakly* autonomous, for they have hardly any bona fide internal representation (specifically referring to representations of type 2 and 3, see Section 2.5, page 58) and consequently are 'constantly pushed around' by the environment (Beer 1995, p. 210).

outside, and that the maintenance of that trait is not easily interrupted, or hard to control, by external factors. For example, organisms are highly autonomous in the resolution of visual boundary, while is less autonomous in the detection of a word from a noisy background which would demand significant support of attention. The memory of a friend's face is not highly autonomous, for the activation of the memory may become difficult as time passes, and as the context of knowing that friend changes.

2.1.2 The Relationship between Autonomy and Adaptability

The notion of autonomy is multi-layered, each layer of which manifests a particular perspective of 'inner drive' that controls the behaviour of individual systems, be they real physical systems (e.g. a pendulum), artificial systems (e.g. a robot ant, or its computer simulation) or living organisms (e.g. a real ant). A subtle property of autonomy is its connection to adaptability. In relation to this connection the different perspectives of autonomy can be analysed, largely along two directions.

According to the dominant metaphysics of nature in modern science – mechanicalism – the autonomy of a system is reducible to the autonomic machinery that controls it. Thus, systems behave like a clock, the archetypal metaphor of single mechanisms. This aspect of autonomy appears in McFarland's cost-based theory of animal behaviour, as we will see in a later section (McFarland 1992). He sees this aspect of autonomy as the operations of a system which is uncontrollable from the external.

In contrast, intuition suggests that human autonomy implies the '*freedom*' of behavioural control from both external pressures and a fully dominant 'internal plan' (Boden 1995, pp. 95, 101).[4] It seems that an internal subtlety is responsible for the autonomy of humans. In addition, autonomy in this sense can also be ascribed to artificial systems where their behaviour appears to be '*adapted*' to the

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[4] The page numbers, here and in the following quotes, are based on the reprint in Boden (1996).

changing environment they inhibit (Boden 1995, p. 101). Their adaptability must originate in the design. For example, the adaptability to a changing environment is manifested in artificial insects, a success in *nouvelle* AI, a new perspective in AI.[5] This new perspective of AI sees behaviour as being determined by the interactions between the environment and the organisms with regard to their low-level operations in the artificial system (Boden 1995, p. 98; Clark 1997).

2.1.3 Autonomy as Freedom

Boden (1995) highlights three intrinsic properties of autonomy, with regard to freedom. First, the behaviour of a system is highly determined by its accumulated experiences, as opposed to environmental factors and the system's innate capacities. Second, the control of behaviour is self-organised instead of being pre-figured by way of design. Last, a system's inner mechanisms can be reflected on or selectively modified by the individual concerned, with the general effect of creativity.

The first property, i.e. the determination of behaviour by experiences, relates to the importance of personally unique activities in the life time, such as idiosyncratic behaviour. It is not hard to realise that behaviour arising in this way is by necessity neither innate nor in-built in any artificial systems. Apparently, they manifest the freedom of individuals from both external factors and the limitation of innate capacities. Individual Experiences, hence, can be regarded as a source of unpredictability, and can accordingly be further considered in the discussion of the third property of autonomy.

The second property, namely self-organisation, as Boden points out, highlights the biological unreality of current AI and ALife study (Kugler 1992), because 'today's computer modelling' is unable to 'allow for "latent" perceptual powers, actualized *only* by newly emerged environmental features' (as reported by Boden 1995, p. 103 in Boden 1996; italics added). The uniqueness of such

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[5] The term '*nouvelle AI*' largely refers to certain newly arisen approaches to studying intelligence, including animat research, dynamical systems modelling, connectionist AI, and the artificial life (ALife) study, in sharply contrast to traditional/classical AI.

newly arisen environmental features can be attributed to the unpredictability of the environment, which leads to a permanent limitation of computer modelling: the self-organising patterns can be theorised as outcomes of systems dynamics; however the actual algorithm would remain un-detected or un-explored.

The third property of autonomy, to wit creativity, as evident in humans, is an unpredictable process of transformation which results in someone being capable of doing something that she not only '*did not* do before' but also '*could not* have done before' (Boden 1995, in Boden 1996, p. 105, italics original). The question is, as Boden points out, what is transformed and how.

Boden places the understanding of unpredictability in the context of AI, a modern technology which is regarded by some as an appropriate way of explanation (Langton 1989). She contends that this property of autonomy can be explained and *modelled* in ALife and *nouvelle* AI. For example, some connectionist modelling includes non-deterministic (stochastic) processes. In addition, she cites a point made by Langton (1989) that in chaos theory a fully deterministic dynamic[6] process may be theoretically unpredictable. The differential equations can characterise and explain a certain change of phenomena. However, the change is not predictable, for no analytic solution can describe that change.

With this (third) property of autonomy being *both* extracted from human intuition *and* explained in ALife and *nouvelle* AI, Boden sincerely reaffirms a claim made previously by Langton (1989) in relation to ALife study but further extended by Boden to *nouvelle* AI: that these two studies provide a mechanistic and a reductivist (but not in the sense of micro-reduction) account of autonomy. Her claim is encouraging for people engaged in these two studies: the notion of autonomy incorporated in ALife and *nouvelle* AI modelling not only does not reduce human self-esteem but, on the contrary, helps us to understand how human autonomy is possible.

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[6] In the present thesis, a distinction is deliberately made between the two terms 'dynamic systems' and 'dynamical systems'. The former term ('dynamic systems') generally refers all systems of which certain relations can be understood in terms of dynamics, such as Newtonian dynamics or dynamic semantics. By contrast, the term *dynamical systems* is specifically reserved for the dynamics characterised by dynamical systems theory, as opposed to other types of dynamics.

Unification in Technology. The above claim, made by Boden and Langton, presents the possibility of offering a unified account of the aforementioned two main aspects of autonomy, namely mechanism and adaptability. These two aspects of human autonomy are usually treated as very different by traditional studies of the mind, such as psychology and philosophy. For the first time, a unified account can be given to them. More importantly, the unification can not only be explained in terms of theoretical constructs, but can also be tested by computer modelling, which lends significant power and accuracy to the explanation of emergence. Also for the first time, technology, as opposed to explanations in terms of mental capacities, is assigned a role in the explanation of the nature of mind. This is, in fact, seen as a new approach to doing philosophy that is propounded by Dennett (1995), who sees this as an advance on the view that philosophy is concerned with seeking the foundation of science (mostly mathematics and physics).

Understanding the Deterministic Processes. The technology, as exploited in ALife and *nouvelle* AI, does not end up as mere instruments which simply *facilitate* conceptual activities. It must stress that the technology is irreplaceable, in the sense that 'we cannot necessarily *understand*' them with regard to the emergence of patterns via such processes, claimed by Boden (1995), although everything here is within the reach of explanation, even within the coverage of computer implementation (p. 103).

To understand Boden's idea, we had better to read the term 'understand' as 'comprehend', because the meanings of explanation and understanding are very close, while Boden does not account for their difference in this particular context – the emergence maintained by machine. A significant difference between them can be identified: explanations can be achieved with recourse to the processes of determination, which may be beyond comprehension. Such a difference especially applies to complex/nonlinear systems, where local activities between components can be described (and hence comprehended) but global behaviours are hardly tractable.

The main reason that the processes of emergence cannot be 'understood', as Boden contends, rests on a unique way of processing inherent in *nouvelle* AI, that the generation of patterns may undergo several changes which 'are made in parallel'.[7] Boden sees that 'it is often impossible to understand' the emergence '*even though* the 'explanation' is available' (ibid.). For example, the flocking behaviour modelled by Reynolds (1987) can be explained, because 'we can see lucidly how it is that holistic flocking results' from the three-rule algorithms (i.e. distance maintenance, matching velocity to the immediately neighbouring Boids, moving toward the centre of Boids in the neighbourhood). Yet, the understanding is restricted to a single change, hence it is impossible to understand simultaneous changes in parallel (Boden 1995, p. 100-3, italics original). Note that the term 'understand' in Boden's context is to be read as 'comprehend', as suggested above.

The process of emergence indicated in *nouvelle* AI can be explained otherwise in terms of nonlinearity. Nonlinear processes of emergence are characteristic of complex systems, as discussed previously (page 22). Because of the nonlinearity, emergence is an irreducible (in the sense of not being micro-reducible) feature of nature, a feature with outcomes predictable as a result of computer modelling, which has understandable *single* steps of interactions between components of the system. It is worth noting that the algorithms of computer modelling explain (via mathematics) how the modelled complex system is *initiated* with respect to the single steps of interactions. Yet, the *group behaviour* remains unspecified. The algorithms characterise the cause-effect of single steps without specifying *which* components *cooperate* with which others in support of which intermediate patterns; nor is there any information about which components would *dominate* which others in the intermediate stages. In addition, the fact that an outcome is desired does not bring about any information as to how the group behaviour is to be figured out in conception.

Algorithms determine a single step of interaction on the basis of the contingent current states before that step, which are not entirely characterisable by those algorithms. When certain algorithms are characterised for a computer

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[7] By 'parallel changes', Boden may mean global behaviour, which seems to be more adequate.

model, they remain to be initiated by environmental factors which will take the form of non-explicit input data in a complex system. Such data are permanently subject to a limitation – unpredictability – of humans, including the designer of algorithms. We humans encounter unpredictable factors in the environment, know that they are to be transformed in the computer model of a complex system, and detect certain desirable outcomes arising in the end. Yet, we remain unclear as to how the unpredictable factors take shape in the intermediate processes of transformation. This is crudely a limitation of human conceptual power.

The process of emergence maintained by computer algorithms is certainly deterministic. However, it is not determined by *us*, but by materialistic and environmental factors (as seen in dynamical systems). We usually detect the regular patterns manifested by nature without understanding how actually nature brings them about. We detect the appearances without knowing the inner mechanisms. By the algorithms of computer modelling, we can find out which pre-conditions of the modelling would lead to which outcomes, but we just let the computer operations fill the intermediate processes, of which the global behaviour is hardly comprehensible. The intermediate processes of pattern transformation are driven and controlled by nature, in particular the materialistic and environmental factors, which are not entirely graspable by our knowledge.

This shows a sharp contrast between ontology and epistemology. The mechanism is deterministic in an ontological sense, but not fully determined epistemically. Such a contrast would be thoroughly conflated in design work (e.g. classical AI), if its theoretical basis closely reflects the reality. Yet, such a contrast turns up strikingly in complex systems, where their intermediate processes of pattern transformation are just let go of until we detect interesting patterns. Several approaches to complex systems take advantage of such a kind of pattern generation, including PDP modelling[8] (e.g. Cliff 1990, 1992), situated robotics (e.g. Brooks 1991a, 1992; Braitenberg 1984; Reynolds 1987), genetic algorithms (e.g. Sims 1991), evolutionary robotics (e.g. Cliff *et al.* 1993), dynamic systems modelling

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[8] The PDP modelling adopts the strategy of design to a high extent (Quartz 1993), but it is also a complex system with regard to the methodology of pattern generation.

(e.g. Beer 1995).

Unpredicability. It is interesting to compare the aforementioned limitation of human conception with another one mentioned earlier in this section, namely a limitation of computer modelling, which also results from environmental unpredicability. That is, although the self-organising patterns in dynamic systems can be theorised as outcomes of systems dynamics, certain algorithms would remain undetected or unexplored. Given that the exploration of computer algorithms would be put in the form of mathematical conceptions, the environmental unpredictability limits the coverage of conception, in both the exploration of computer algorithms and the understanding of computer modelling with regard to its intermediate processes of information transformation.

Trade-off. Despite the above claim made by Langton and Boden, the two aspects of autonomy – mechanism and adaptability – are not always unifiable. Langton and Boden both present a prescriptive understanding of the mechanism-adaptability relationship, that adaptability *must* be incorporated in the mechanisms we aim to explore. Langton prescribes a *goal* for ALife study, while Boden presents the case in humans as a goal of theory or modelling. There is indeed a permanent trade-off between the already explored mechanisms and the expected adaptability. We are not yet aware of how evolution incorporates adaptability into autonomous mechanisms, while it is not difficult to realise that adaptability is a ceaseless challenge to engineers. In engineering there is no such a thing as a universally effective module, as is well understood in classical AI. As is pointed out by Pfeifer (1996), there is a well-known trade-off between generality and direct applicability. This is a matter of fact in engineering. Although evolution results in autonomous organisms which are capable of accomplishing open-ended tasks, that is indeed a challenge in engineering (Beer 1995).

2.2 Ecological Niche and Intelligence

2.2.1 The Notion of Ecological Niche

Ecological Niche. The term *ecological niche* refers to the functional position of the species in the environment, comprising the habitat it resides, the time it is active there, and the resources to which it has access (Allaby 1994); alternatively it refers to the functional role of a species in a community, consisting of its relationships to other organisms and the physical environment (McFarland 1992). Thus, the ecological niche of a species consists in the species' relationships to the environment's *abiotic factors*, its behavioural propensities within the environment in which it resides, and the *behavioural relationships* it consequently develops to its conspecifics or other species in the same environment. Ecological niche is the epistemological basis for the study of the evolution of a particular species regarding its evolved biological structures, functions, and psychological capacities on the one hand, and the principles of their emergence on the other.

Note that the aim of the present thesis focuses on the linkage between two tendencies of activities, while the linkage by nature presents a merge between two tendencies of activities. These two tendencies are: (i) how the ecological niche of a species is incorporated into organismic systems in the form of cognitive structures and functions, and (ii) how such structures and functions are brought about on the basis of the self-regulating activities of the organismic physiology. In brief, the former approach is exogenous, while the latter is endogenous. We can see these two tendencies as two sides of emergence.[9]

2.2.2 McFarland's Cost-based Theory

In this subsection we introduce a theory which relates organisms' behaviour to its ecological niche. This is McFarland's (1992) cost-based theory of robot and animal behaviour, which has two central tenets. First, he claims that animal

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[9] A linkage between these two sides is provided in the present thesis in the discussions centred around the notion of *inverse ecological niche* (see Section 6.5.1, page 255).

behaviour is governed by mechanisms which are *optimised* through evolution with respect to the *real costs* that are characteristic of the animal's ecological niche. In response to its ecological niche, an individual animal will develop a certain *value system*, an acting cost function which is an arrangement of goals subserving the reduction of costs. Subject to individual differences, this value system is in agreement with the real costs of its ecological niche. The closer the value system is to the real costs, the more likely the individual is to survive.

The value system of an individual animal, according to McFarland (1992), consists of its optimality principles – those principles which control animal behaviour. However the animal behaves it tends to obey such principles in the end, like the trajectory of physical objects which obeys a 'least action' law by minimising a particular function of kinetic and potential energy (McFarland's quote). the optimality principles manifested a somewhat teleological sense of behavioural confinement. As McFarland puts it, such principles, on the one hand, 'are, *in effect*, functional explanations which describe how the animal *ought to* behave in order to attain some objective' (p. 197, emphases added). They are 'motivational' tendencies under competition 'for behavioural expression' (p. 196). The optimality principles also take the form of causal explanation, such as 'a set of rules of thumb', which is 'the equivalent of physical forces' (p. 197).

Cause-effect Principles vs. Teleological Characterisation. McFarland's idea of optimality principles can be understood as causal laws[10] according to which the animal behaves *as if* it holds certain teleological ends. Teleological understanding is intuitive. Certain physical phenomena can be so understood intuitively. For example, by analogy with the experience that humans generally

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[10] McFarland regards the cause-effect mechanisms of animal behaviour as the very characteristic that qualifies animals as being cost-based robots, because they manifest deterministic principles. For this, the mechanisms that govern animal behaviour and robots are 'no different in principle' (McFarland (1992), p. 192). He seems, strictly speaking, to confound the cause-effect confinement with deterministic characterisation. Stochastic mechanisms, to put it in a critical case, are subject to cause-effect principles but are not deterministic. Teleological confinement may take the form of deterministic rules, but does by no means conform to cause-effect characterisation. What really matters in McFarland's theory, crudely speaking, is the non-teleological characterisation, i.e. cause-effect confinement. Determination, in the comparison between animal behaviour and robots, is irrelevant.

pursue higher social status, water is understood as *seeking* to go downward. In brief, the teleological understanding can be simply taken as an analogical understanding of the cause and effect relationship.

The distinction between cause-effect principles and their teleological analogues is important in the study of animal behaviour, in which evolutionary explanations and ecological considerations play a central role. It is important not only because evolution and ecological interrelations remain fundamentally mechanical despite their teleological appearance, but especially because the teleological terms in consideration of evolution and ecology, quite often, disclose certain *natural* tendencies of organisms.

The ecological niche of organisms seems to have a strong connection to the manifestation, in ontogeny, of their respective intentional pursuits. Because deer require water, for example, they develop an overt intention to seek water. Although the *underlying principles* of animal behaviour remain rooted in the ecological niche, as opposed to the intentional pursuits, such a strong connection *makes sense of* the teleological characterisation of animal behaviour. Accordingly, mechanicalism and teleology can be regarded as two parallel perspectives of understanding. This may be the reason that the teleological characterisation of animal behaviour is difficult to eradicate: teleological terms make sense of ecological niche indirectly, but informatively and accurately.

Autonomous vs. Rational Dimensions of Value System. The second tenet of McFarland's theory is that cognitive systems manifest their flexibility not only in a fully autonomous dimension, but also in a rational dimension, where planning and learning may take a role. These two dimensions, McFarland (1992) points out, are usually present simultaneously in any single organism. They can be taken as a duality of cognitive capacities. Such duality also applies to perception.

1. Implicit Value System Manifested in the Autonomous Properties of Perception. The autonomous properties of cognition, as McFarland (1992) argues, provide many facilities that meet the needs of the ecological niche. They are effective, quick in response, subserving the primary demands of survival with respect to a particular ecological niche.

2. Explicit Value System Manifested in the Rational Properties of Perception. The downside of such autonomous capacities, however, is their lack of flexibility in the consideration of planning activities, which generally present in daily-life perceptual tasks, such as going across a street and looking for a lost bag. In fact, the relatedness of perceptual activities to *planning* is a main source of organisms' adaptability. Organisms can accordingly manipulate perceptual capacities, whatever the degree of autonomous flexibility they may possess, in order to *observe* the *relevant* circumstances with a view to fulfilling the need of certain goal-oriented decision-making activities. Relative to different goals and local environmental conditions, the maintenance of perceptual tasks needs to be adaptable to different emphases of their expectations, and the degree of adaptability even need to be improved by learning.

For example, for satisfying the expectation of safe passage in a predator area with certain hiding places, such as caves, prey need to make available the resources of attention and memory-access. To put it in the context of McFarland's cost-based theory, the prey have specific ecological niche, on the basis of which a set of cost functions is defined which accordingly reflects the evaluation of that ecological niche. Different prey may adopt, in fact pre-fix, different value systems to derive their respective strategies of survival. In an attempt to reduce their cost in their respective avoiding predator activities the prey must learn to improve their skills of escaping or the proficiency of observation, e.g. by inducing certain important cues of the predator's behavioural patterns in addition to their (the prey's) autonomous facilities.

Note that the task of avoiding predator in a predator area assumes certain environmental conditions, against which the agent needs to make available certain relevant information in memory and a high degree of attention. Also note that whenever the prey start to go across the envisaged area they will soon be detected by the predator, hence what is critical to the success in avoiding predator behaviour in that dangerous area, apart from their respective running abilities, would be the competence to find out intermediate hiding places in an attempt to escape the predator's chase. Consequently, the prey can learn to reduce cost by reviewing their experiences in memory to ensure, for later use, a minimum requirement of time for a predator to catch them. The prey can take advantage of such a minimum requirement of the predator and can accordingly learn to start a running effort toward a next hiding place, by ensuring beforehand that there is really no predator lurking around at the moment.

This is certainly a task in need of higher adaptability than the flexibility manifested in the autonomous capacities. To attain such a high adaptability, organisms need to learn on the basis of their capacities of attention, memory, the calculation of speed, and the judgement of predators' presence, with a view to reducing the costs against the pre-fixed value system. Thus, McFarland's cost-based theory may well apply to the domain of perception.

The Notion of Autonomy. Autonomy is seen by McFarland (1992) as a requirement of cost-based mechanisms, because an individual (real or artificial) organism must be able to maintain its behaviour effectively, so that it can respond to the challenges arising in its ecological niche with the 'freedom from control' to a certain extent (p. 191). Specifically, the control of organism behaviour *can be entirely* subject to the self-determination maintained in the internal mechanisms of the individual at issue, while there is a core mechanism that *can only be* carried out by the individual organism itself. In this regard, McFarland presents the notion of value system, which, as we introduced previously, serves to determine the behaviour of an individual animal, by reducing optimally the real costs for the individual organism to live in its ecological niche.

The notion of autonomy may have a strong connection to mathematical modelling. Note that the notion of real costs with regard to a particular species is a property of its ecological niche. The optimality of reducing costs, hence, manifests the greatest adaptability to its living environment. Thus, the notion of autonomy includes the adaptability to the environmental challenges. The traditionally presumed paradoxy between autonomy and adaptability is conflated with the cost function pertaining to particular ecological niche, depending on what species is in question. Also note that either the cost function or value system can be managed both qualitatively and quantitatively. Accordingly, the settlement between autonomy and adaptability is resolved nicely in McFarland's cost-based theory, in the sense that it can be cast in well-defined categories and then put into mathematical modelling, with the aim of either exhibiting systematically the realities of the species' particular ecological niche or reflecting analytically the regarded individual's ways of behavioural control in that ecological niche. As a consequence, both the notions of ecological niche and individual behavioural control can be subject to mathematical modelling, in support of the notion of autonomy. This is an apparent contribution by McFarland to the notion of autonomy in the study of ALife.

In sum, McFarland's cost-based theory of animal behaviour provides an ecological foundation for evolution in relation to animal behaviour, a foundation which serves to explain the autonomy of behavioural competence, to the extent that the autonomy can be implemented by mathematical modelling.

Criticism of McFarland's Theory. McFarland's cost-based theory of animal behaviour has its limitations. First, each capacity of living organisms has its own processes of emergence; however, his theory is essentially a *functional characterisation* of a simple case and hence has no bearing on the theme of emergence. Although McFarland mentions the contrast between autonomy and adaptability which is a core issue in the consideration of emergence, that contrast can also be considered in the context of design, regardless of the process of emergence out of natural constraints. It may be because McFarland emphasises the equivalence between organisms and robots that he focuses on specification of animal behaviour but eschews entirely the issue of its emergence.

Second, his theory is designed to explain bodily actions, with bomb disposal as the archetype of its targeted phenomenon, but it disregards the domain of perception. Although the relationship between bodily actions and perception is central to active perception research and a recent trend of cognitive neuroscience (Churchland *et al.* 1994), the relationship of perception to bodily actions, and in turn to ecological niche, is left untouched in McFarland's theory.

Third, both value system and cost function may be subject to change, but McFarland supposes them both to be fixed. It is not difficult to understand that individuals of certain species, e.g. humans, are likely to adopt successively different value systems in their life time. McFarland seems to aim to characterise the *essential* factors of animal behaviour, by denying the possibility of its *change* throughout ontogeny. The previous introduction of McFarland's cost-based theory into the study of emergence would be incomplete, unless the deficiencies manifested in the above three problems could be addressed.

2.3 Brooks' Subsumption Architectures

Brooks' *Situated* Approach to Mobile Robotics. Brooks' situated robotics is the earliest version of reactive robotics (Arkin 1995). It is not intended to model intelligence, but to perform it. With performance as the outer aspect of intelligence (as opposed to internal model), this approach serves to demonstrate that intelligence, including avoidance, wandering, and higher-level activities, can be built in the style of *activity-producing layers of control.* This is the main methodology of Brooks' approach, of which the characteristics are discussed below.

Brooks' notion of subsumption architecture is grounded on his three-layered robot, with details as follows.

Layer. A *layer* is a single unit of activity-producing control, composing of a fixed (strictly speaking, *pre-fixed* by hand) network of certain simple finite state machines, as seen in Brooks' earliest two robots Allen and Herbert (Brooks 1991a). A single layer, by definition, is primarily a behaviour-based design. That is, each layer necessarily serves to produce a specific activity, such as avoidance, wandering, catching a can-sized object (the tasks of Allen's three layers respectively), and global direction determination for finding soda-can-like objects (one of Herbert's tasks).

Inter-layer Communication. Between layers, there is no *central* locus of control for inter-layer communication.

Organism-Environment Interaction. Between a robot and the environment it encounters, there is no memory and no learning, and hence '*no representations*'[11], as Brooks claims.

Real-time Response. The situated robots must respond to their situated environment in real-time (e.g. within 3 seconds for Herbert – a hand-crafted requirement, not established by natural selection) (Brooks 1991a).

Subsumption Architectures. Layers are built incrementally, according to *subsumption architectures*, which requires the layers to be decomposed by specific activities, and be combined incrementally by implementing the lowest layer first through *debugging* in the real world, then implementing the second one, also through debugging, and then the third, and so on.

A Comparison between Situatedness and Embodiment. The notions of embodiment and situatedness both uphold the importance of direct contact with the environment, as opposed to maintaining searching on the knowledge representations of a world model. Yet, these two notions are different: briefly, the notion of situatedness concerns organisms' relation to the environment, while the notion of embodiment concerns the effects brought about on account of organisms' bodies.

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[11] The term 'no representations' seems to be too strong and somewhat inappropriate, because the subsumption architecture actually assumes certain types of internal representations (types 4 and 5, see Section 2.5, page 58). What Brooks really aims to argue against seems to be the internal representations adopted by traditional AI, which fall into the categories of type 2 and 3.

Situatedness. Being situated, behaviour-based systems count on rapid contact with the various aspects of the environment without undergoing a long path of search over a world model. The organisms intensively contact various aspects of the environment, by confronting with and wandering between various situations. As Brooks describes, such systems continuously refer to sensors rather than maintain searching in the internal model. Information from sensors is, and must be, responded to 'in a very short time span' (Brooks 1991b, emphasis added).

The situated[12] robots, as Brooks claims, must develop in the *real* environment.

Embodiment. Being embodied, a behaviour-based system gathers information based on various *effects* of its *body* which are evoked when the system contacts the environment: including the sensory features provided by their sensors, the movements of their bodies, and the new relations with the world created by their bodily actuators or posited by their sensory-motor actuators. In this regard, Brooks contends that in order to gain precise understandings of the world, '[a]ll the details and issues of being in the world must be faced' (ibid., p. 15). It is worth noting that those 'details' include two remarkable unpredictabilities: the mechanical (without being entirely mediated by information of certain categories) bodily effects evoked by unpredictable environmental factors (as exemplified by the effects brought about by the automaton *avoid*), and the bodies' somewhat unpredictable spatial/geometric and temporal relations to various aspects of the environment (as maintained by the automaton *wander*).

In contrast to traditional AI, no internal model is adopted to characterise robots' capabilities. As Brooks claims, if there must be a model resting between the robot and the world, '*the world is its own best model*' (Brooks 1991a, p. 417, italics original), a famous aphorism of Brooksian robotics which can be rephrased more clearly: the situated robots, on the basis of their reactive modules (such as the automata in the three-layered architectures), gain capabilities from

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[12] The conception of situatedness is sometimes termed as 'embedment'. As a consequence, the situated and embodied agents are called embodied and embedded agents.

the reactive activities in response to various (even unpredictable) environmental conditions.

On account of such reactive modules, Brooks' situated robots circumvent the grounding problem of internal representations (see detailed discussions in Appendix B, page 358), although the subsumption architectures can be regarded as internal representations in a certain sense (type 4, see Section 2.5).

The Subsumption Architecture of Reactive Robots. The performance of Brooks' situated robots in general is reactive. The lowest layer of Allen, namely **avoidance**, is purely reactive. It consists of simple finite state automata, in order to detect repulsive forces, turn and move forward, or to detect a dead object in the way and halt. By contrast, the second layer (i.e. **wandering**) is somewhat less reactive, as Brooks admits. This layer is added on the top of the lowest layer, connected by certain wires between layers.

A priority of functionality is pre-fixed with respect to these two layers: the upper layer is functioning only when the lower one is not busy. The functionality of the wandering layer is initiated by generating a random heading every ten seconds or so, from a finite state machine *wander* (not the wandering layer, although their names are easily confused). To decide whether the lower layer is busy in avoidance, in this (second) layer a finite state machine *avoid* (not the avoidance layer) takes the heading as an attractive force and sums it with the repulsive force detected in the lowest layer, which was passed beforehand to the *avoid* finite state machine via a wire between layers. If the information shows the lowest layer is busy, the control of the robot is dominated thoroughly by that layer, and consequently the impulse of heading, generated by *wander* in the upper layer, is entirely ignored. Alternatively, if the information from the lowest layer does not show it (specifically the *turn* and the *forward*) as being busy in running the robot, the *wander* (of the second layer) remains functional and the result of summing modifies the heading and thereby drives the robot forward in a direction avoiding obstacles.

The functionality of this two-layered robot is still reactive, but is generally constrained by the connection between layers as described above, with the pre-fixed priority of the functionality between layers (controlled by the *avoid*) as the main constraint of the reactivity.

The third (top) layer serves to explore objects to catch, comprising two automata – *pathplan* and *integrate* which subsume to a pre-fixed *priority control*. There are wires connecting the top layer to the wandering layer and to the avoidance layer respectively. First of all, this layer suppresses the second layer to see whether the lowest layer is busy in avoiding obstacles. If it is not so busy, then it sees whether the second layer is busy in driving the robot movement. If not, it suppresses the wandering layer and tries to explore objects to catch, by the *pathplan* finite state machine, i.e. automaton. Simultaneously, it directs the information of the *pathplan* to the *avoid* finite state machine, that makes the lowest layer continue to function. The information from *avoid* is sent to *pathplan*, with the effect of *modifying* the direction of robot motion. The modification is monitored by another finite state machine *integrate* that sends updated estimates to *pathplan* for further exploration.

In spite of the above constraints (note the modifications) between layers, the three-layered robot is still a reactive robot. Each layer has its specific activity to perform, and the three layers are combined by the priority constraints as described above. Those constraints distribute information across layers, with certain activities being stopped or modified, resulting in the smooth functioning carried out by the three-layered robot which aims to perform different activities (detecting obstacles, avoid, moving forward, explore objects) with the incrementally added three-layered subsumption architecture.

Partially Reactive Robots. A mobile robot (note: not necessarily a Brooksian robot) may be *partially* reactive, in the case where its control system comprises certain representations of the external world, on the one hand, and its activities cannot be determined until it contacts the environment directly, on the other. In such circumstances, it would still make sense to understand embodied robots and embedded activities. They can be understood *insofar as* the robot in question is reactive. Most mobile robots at present seem to be partially reactive.

For example, autonomous agents fall into this category. As we show in this chapter with the architectures in Maes (1990b) and Steels (1990a), internal representations are adopted, and reinforcement learning algorithms are used to maintain internal models. However, the control of robot activities is not entirely determined by the search over internal representations such as the attempts in traditional AI.

What is important for the present thesis is the fact that most, if not all, implementations of active perception fall into the category of partially reactive robots, as we will demonstrate in chapters three and four.

To summarise, Brooks' situated robots adopt incrementally layered subsumption architectures, with the priority of functionality imposed across layers on various automata, resulting in reactive activities being modified and thereby the robots performing smoothly.

Criticism of Brooksian Robotics. Brooksian robotics has far-reaching impact on philosophy of emergence. Several accounts of emergence (Clark 1996; Varela *et al.* 1991; Hendriks-Jansen 1993) undertake the externalist stance of emergence – conceiving emergence solely in terms of organism-environment interactions. They all adopt Brooksian robotics as their empirical support.

Brooksian robotics may well support a claim of externalism, but such a philosophical account would only be tenable insofar as Brooksian robotics is applicable to cognitive behaviour. However, its scope of applicability is limited to reactive behaviours. As Aloimonos (1993) points out in the introduction of his edited book *Active Perception*, 'Brooks' viewpoint that world can be used as a repository of information can give rise, at best, to some simple reactive behaviors' (p. 8). Brooksian robotics, as is manifested in the notion of subsumption architecture – incremental layered control of reactive automata, has no bearing on high level intelligence which requires representations, memory, or learning. It is on account of such *internal* connections that organisms gain sufficient flexibility in their development of non-reactive skills. In this regard, interaction with the *world* does not seem to be promising in the emergence of flexibility.

The world is undeniably an indispensable resource of emergence, but it does not itself organise emergent behaviours. It is, rather, cognitive capacities and relating motor activities that organise, whatever the level of an emergent behaviour is. They maintain subtle feedback loops between them *and* the world, and thereby organise emergent behaviours. If there is no reactive action automata, there would be no emergent behaviour of navigation shown in Brooksian robotics. Similarly, there cannot be high level emergent behaviour at all, if there are no sufficient subtle cognitive capacities and relating motor activities to maintain sufficiently informative feedback loops.

2.4 Exploitative Control

2.4.1 Exploration and Exploitation

The contrast between exploration and exploitation can be understood in a broad context – mobile robotics – or in a narrow context – systems that change positions to facilitate knowledge acquisition or problem-solving (henceforth *active systems*[13]). In the broad context (i.e. mobile robotics), they are two strategies of action manipulation. Exploration is about certain actions that drive the mobile robots to contact different positions/states of the environment, for collecting information or performing certain actions. Exploitation, in contrast, concerns setting *constraints* in the internal states of robots, by introducing heuristic knowledge of the collected information. In the narrow context (i.e. active systems), they are two different strategies of action *selection*. Given the limitations of space, the present thesis is put in the narrow context. As a consequence, we will focus

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[13] According to this meaning of active systems (systems that change positions to facilitate knowledge acquisition or problem-solving), active perception systems are active systems. Active perception systems, as defined in chapter 1, change the positions of bodies and sensory organs in order to improve the capabilities of perception. Such a meaning of active systems can apply to *active learning*, as discussed in Thrun (1995).

our discussions of exploration and exploitation on active systems.

Exploration. Exploration is a strategy of action selection for *active* systems, according to which organisms inspect/explore those aspects of the environment most relevant to the required tasks, by arranging the *action modules* of the systems in parallel or in certain serial orders. Such an understanding of exploration relates to two categories – the environment and action modules. Several questions would arise. On the environment side, an active system encounters a central question: which aspects of the environment are most crucial for (i.e. relevant to and relatively sufficient for) the required task? To frame it in another way, how do we maximise the knowledge gain for the required task? On the side of action modules, the active system needs to resolve a variety of questions: in order to inspect the most crucial aspects of the environment, how does the active system manage to derive appropriate actions on the basis of the available action modules? Can those crucial aspects be derived at the same time, or should they be made clear gradually on the basis of previously derived *information* (i.e. 'knowledge gain'; see Thrun 1995, in Arbib 1995, p. 381)? Can they be carried out within a plan of appropriate actions, or should the appropriate actions themselves be made available gradually on the basis of the previously performed *actions*. Indeed, it is usually the case, e.g. saccadic movements, that which aspects (of the environment) need to be explored cannot be determined until certain actions (the saccades toward certain positions of the visual scene) have already been carried out.

The Focus of Exploration. Two assumptions are seen as important *in theory* for exploration with regard to learning tasks (Thrun 1995), but they can be extended to exploration in general. Firstly, there must be heuristics for estimating the knowledge gain so that the estimation is approximately correct. Secondly, the activities of gaining knowledge, i.e. the inspection of the environment, must actually contribute to the tasks in question. In other words, such activities must be most relevant to the tasks, given that the computational resources of organisms (such as time and working memory) are constantly limited for accomplishing tasks in the real environment. In brief, the two requirements for exploration are the *correct estimation* of knowledge gain and the most *relevant activities* of gaining knowledge.

These two concerns may not be achieved easily in practice, as Thrun (1995) reports. In order to improve the effectiveness and efficiency of exploration, i.e. bring exploration into 'focus', certain '*task-specific utilities*' are adopted *in combination with* exploration (ibid., p. 382).

Exploitation. The strategy of maintaining the aforementioned task-specific utilities is termed exploitation. More strictly, exploitation is the use of *constraints* in the *internal states* of active systems, in support of the exploratory activities in the environment, for promoting the effectiveness and efficiency of accomplishing the tasks.

The Distinction between Exploration and Exploitation. A caveat must be made concerning the above account of exploration and exploitation. It would be a mistake to distinguish them via the categories of *external-vs.-internal* processes – that is, roughly relating exploration to external processes and attributing exploitation to internal control. This would be a mistake for two reasons. First, different explorative processes may differ in their degree of internal control. Specifically, exploration can be either purely random, or *directed* under certain *a priori* heuristics that drive an active system to certain positions in the environment in order to collect information with optimised knowledge gain. Such heuristics must be implemented within a system, i.e. implemented as *internal* control. For example, explorative processes may be directed to regions with the largest estimated error, less explored states (such as visiting the least recently inspected positions), or the planning action for exploring global states (instead of visiting the local state with the next nearest sensations) (reported by Thrun (1992)).

Second, the heuristic knowledge for exploitation may be provided externally (from outside the system) or derived internally (from within the system). For example, the *a priori* knowledge for pursuit movement and the templates adopted in Kalman filter are externally provided. By contrast, the critical variables in Adept (see Section 4.2.1, page 126) for computing a route toward a target are hand-crafted (i.e. externally determined), but their values are computed internally.

A salient distinction between exploration and exploitation rests on the different questions they relate to. Heuristic knowledge needed for exploration concerns *what actions to take* or *where to visit.* In contrast, the heuristic knowledge for exploitation concerns *intermediate* control for deriving appropriate explorative processes, such as the heuristics for resolving the questions where *the target object* (not the active system *per se*) would be most likely to go, what features the visual *object* has (in Kalman filter). In other words, the heuristic knowledge for exploration provides *a priori* suggestions as to what the *active system itself* needs to *do* next, while that for exploitation initiates *a priori* indication as to what the *object features* is most likely to *be*, without determining any behaviour of the active system directly.

A Consideration of Efficiency. An active system incorporating the combination of exploration and exploitation, as demonstrated by Thrun (1992), runs much more efficiently than *random* exploration. In the experiment, the task is for the robot to navigate from a specific position, in the environment with obstacles, toward an envisaged (by the designer) target. As a rule of this experiment, the robot should return to its initial position once its crashes; that is, it should restart the experiment. The difference between random exploration and the other is the learning (maintained by a reinforcement learning algorithm) to avoid the previous crashes.

As a result, in 15,000 runs the robot with random exploration crashes 14,991 times, while that with the combination of exploitation and directed exploration only crashes 4,000 times, which is relatively successful. This experiment shows that the *selection* of processes maintained by the combination of exploitation and directed exploration indeed facilitates the learning of a navigation task. Although this experiment is specifically designed in the context of learning navigation, which is a particular active system, this experiment may be taken as evidence supporting the view that active systems can be generally facilitated by the combination of exploitation and directed exploration, as opposed to random exploration. In other words, the heuristic knowledge for exploration and exploitation facilitates the selection of processes, which in turn facilitates the performance of active systems.

2.4.2 Steels' Account of Emergent Functionality

The notion of emergent functionality is employed by Steels (1991) to explain the process of emergence within behaviour-based systems. This notion provides an explanation of two issues – the importance of organisms' adaptability and the part-whole (local-global) relationship in the process of emergence.

Organisms' Adaptability Contributes to Emergence. Consider the first issue. The course of emergence involves the dynamics within the environment and the adaptability of organisms, as demonstrated by Steels' implementation (1990a), which demonstrates emergent foraging behaviour on the basis of exploitive control (see Section A.1, page 343).

According to the architectures of Steels' implementation, the environment is dynamic, because the food sources may be moving. The autonomous agents have a certain degree of adaptability, as is evident in the appropriate combination of many activities, which comprise the functionality of comparison between the immediate inputs and the expected food type at the expected food location, the identification of target food sources by waves of various types, and the derivation of routes by the emanation of gradient field. If certain obstacles are detected on the way toward the target, a *subgoal* can be setup for removing those obstacles, before the robot bumps into the obstacles on its way toward that target. Since the environment is dynamic, the autonomous agents must adapt their activities against changes in the desired objects or the obstacles. It is apparent that emergent behaviours without significant adaptability to environmental changes would be unsatisfactory. Fortunately, the exploitative control of Steels' implementation, i.e. forage, presents significant adaptability in response to environmental dynamics. Hence, we find that the adaptability performed by organisms is a requirement of behaviour emergence. The autonomous agents must adapt themselves in the course of working out the emergent behaviours, to the extent that the emergent behaviours direct those agents to survive the environmental changes/dynamics.

Implicit Determination of Global Behaviours. Consider the second issue – the part-whole (local-global) relationship in the course of emergence. An intriguing issue of emergence is the question of why local activities lead to global behaviours, given that those global behaviours are not directly characterised in design. One approach is the attribution of emergent functionality (as global behaviour) to the instructions/scripts of implementation, which determine *local* activities in the process of emergence. The main reason behind such an approach is that the implementation of the concerning emergent behaviours is *fully determined* by those instructions. Such an account, however, is denied by Forrest (1991), because those instructions do not account for emergence at the global level. He sees those global behaviours as being determined *implicitly*, while the local activities are specified explicitly.

A further argument against the suggested approach can be cast in terms of *environmental conditions*: the instructions of local activities do not really fully determine the emergent behaviours, because it is those instructions *together with the environment* that determine the emergence in question. The same set of instructions, when they are applied to a different niche, may lead to different global behaviours. As an extreme case, a robot fish would simply lie idle on land. Without a certain niche being fixed, a certain global behaviour would not be fully determined.

These two challenges to the above attempt (the attribution of global behaviour to the instructions/scripts of implementation) seem to be adequate. Yet, the question of explaining emergence remains, because the ground conceptions 'determined implicitly' and 'global behaviour' are pretty vague. Such terms only serve to show that the *local* instructions do *not* explain the emergence. Yet, the argument of the above challenges is based on *negative* terms (i.e. 'determined *implicitly*' and '*non*-local behaviour') without positive characterisation, because those terms *per se* do not assert any requirement to account for the question of how actually the emergent behaviour arises.

Emergent Functionality. Steels' theory of emergent functionality sheds some light on this question. Steels (1991), like Forrest (1991), does see the functionality of a single component as a sub-function of the global functionality. The emergent global behaviour is brought forth by the functionality of those components together as their 'side effects' (Steels 1991, p. 454). Again, 'side effect' is a negative term, which has no positive requirement for explaining emergence.

Steels' theory, however, has more to say about the determination of the emergent functionality. He emphasises the importance of the environment, in mediating the emergence of the global behaviour. By introducing the mediation of the environment in the course of emergence, Steels holds out the possibility of giving a more specific account; however, this will require a clearer treatment of the role of the environment, as we will see.

Steels maintains that the mobile robot operates directly on environmental parameters and that the different components of the robot system interact directly; by contrast, they contribute indirectly to the emergent functionality, with the mediation of certain auxiliary structures (such as the growth substances – e.g. heat – for a growing tree) which are generated in the environment. The mediation of the environment should not be overlooked in an explanation of emergent functionality. Such a consideration is applicable to rock collection robots and a wall-following robot, but tends to be inappropriate when it is applied to the growing tree system, which are the three examples that Steels adopts in support of his theory of emergent functionality (see Section 2.4.2, page 45).

1. Rock Collection Robots. The implementation of the rock collection robots (Steels 1990b) is inspired by ant colonies. The system presumes a fixed field in which robots are moving. The robots put down crumbs when they detect food samples. Between the left crumbs and their nest, they establish a zone that attracts other robots. This system is specified by the following instructions. Before we review these instructions, a note must be made in order to understand Steels' implementation more easily: the food sample may disappear, for other organisms may take it away without touching the previously dropped crumbs. Hence it is not surprising that a later-arriving robot may detect crumbs without finding the food sample.

The instructions, then, are as follows:

- **Random Movement.** A robot in this system moves at random through the field.
- **Obstacle Avoidance.** When a robot encounters an obstacle, it stops and turns away from the obstacle.
- **Path Attraction.** When a robot detects the crumbs, it moves toward them.
- **Sample Collection.** When a food sample is detected, a robot picks it up.
- **Crumb Handling.** In the place where there are crumbs, if a food sample is gathered, two crumbs are dropped; otherwise, when no food is detected, pick up one crumb (which must have been left by a previous robot).
- **Vehicle of Collection.** When a robot stands at the vehicle for food collection and has gathered a food sample, drop it on the vehicle. If a robot encounters the border of the exploration field, it turns around.

It is clear that the wandering robots in this system would eventually gather all the remaining food samples (which have been previously detected) and drop them on the vehicle, and consequently the task of this implementation is accomplished. The accomplishment of the task in question, needless to say, relies heavily on the previously dropped crumbs in the common field. Steels' notion of environmental mediation, then, is clearly applicable to this system. In this case, the notion of environment is clear, because basically a fixed field of robot movement is given beforehand.

2. Wall-Following Robot. The notion of environmental mediation can be seen equally in the case of a wall following robot (Mataric 1990). Its instructions are specified as follows (italics added):

- *Stroll. When there is no obstacle in front,* move forward in a more or less straight motion. *When the robot encounters an obstacle,* stop, and follow the instruction of **avoid**.
- *Avoid. When there is an obstacle in front,* turn right or left.
- *Align. When the distance to the object behind is shorter than the distance in front,* turn by a small angle.

According to Mataric (1990) (as reported in Steels 1991), the experiments for four runs (Mataric 1990, p. 53) show the emergence of consistent boundary tracing out of the above three instructions. Steels concludes that his notion of environmental mediation has been supported, because the data flow of robot interactions is clearly mediated by the environment, as is evident in the above italic phrases.

What precisely the environmental spatial conditions will be depends on the contingent environmental conditions and the somewhat random movements of the robot. However, the robot activities only take advantage of the resulting spatial allocations, because the above italic phrases are *pre-conditions* of robot action selection. Whatever the eventual spatial relations turn out to be, and whatever actions a robot may take, the action must be pre-conditioned by the immediate spatial conditions. Given that there is one common environment, the notion of environmental mediation is also clear, although the ways of mediation are different. In this system, the environmental mediation is not realised by the detection of crumbs, but is alternatively realised by the spatial relations between the robot and the boundary of the given field (the walls). So far, Steels' notion of environmental mediation remains applicable to the course of emergence.

3. Tree Growth System. His notion, however, seems questionable in its application to the case of the tree growth system (Steels 1990b). The instructions of the tree growth system are specified as follows:

- **Food Diffusion** Food from the root diffuses at a certain rate across the cells of the tree, across the stem, left-branches and right-branches.
- **Increase of Growth Substance** Depending on the availability of food, the growth substances increase in amount.
- **Generation of Cells** When the amount of growth substance passes beyond a certain threshold, a new cell of the tree is generated.
- **Inhibition Over the Further Increase of Growth Substance** The presence of a cell, be it a cell of the stem, left-branch or a right-branch, will inhibit the further increase of growth substance over there.

While the food supply continues, the increase of growth substance (and consequently the generation of cells) will not be overwhelming in a certain direction, but will be balanced between the left and the right branches of the stem. The components of the tree growth system take as inputs food and the growth substance; in addition, they generate their own outputs, such as the increase in the amount of the growth substance. Notice that food is passed *directly* from the root across the tree, to the left and right branches of the stem, without the mediation of the external environment. Similarly, the growth substances increase, when they are nourished by the arriving food, without the mediation of the external environment. Similarly, the generation of the cells, when the amount of growth substance rises beyond certain thresholds, occurs without the mediation of the external environment. Steels contends, however, that there is communication between such components, and that it occurs *via the environment*, e.g. by the presence of growth substance. At this point, Steels' claim of environmental mediation does not seem to be supported, because nothing has passed through the environment. The only possible exception is the beginning supply of the food. Yet, the beginning supply is really not mediated by the environment at all. All further processes have no connections with the environment. We can therefore conclude that Steels' notion of environmental mediation does not apply to this case of behaviour-oriented agent implementation.

No Mediation of the Environment Found in the Exploitive Control of Steels (1990a). Apart from its inapplicability to this implementation, the notion that emergent functionality needs the mediation of environment is also inapplicable to Steels' own implementation of *internal* representation exploitation, which we previously discussed (Steels 1990a). The information flow only passes through the two grids, which consist of purely internal representations. The initial inputs come from the (external) environment, but there is no further contact with the external environment. All the representations dealt with are internal ones. If the notion of environmental mediation is applicable to this particular implementation, the two grids must be conceived of as internal environment, as we previously suggested. Crucially speaking, the environment, which mediates information flow, is the common arena (field) of the interacting components. Steels' notion of environmental mediation should accordingly be modified.

Beyond Steels' account, the explanation of emergent functionality needs more further development. In this regard, the present thesis will provide some more explanations, as seen in chapters 6 and 7.

2.4.3 Steels' Criticism of Reactive Systems.

Based on reactive interactions between organisms and environment, Brooks (1991a) dismisses the need for internal representations in the design of intelligent agents, which he maintains would still be capable of evolving into full-fledged cognitive organisms. Those reactive interactions are local activities but may eventually lead to global behaviour, as demonstrated in a broad range of behaviour-oriented implementations. Brooks' claim has had immense impact on views of emergence: the implementations in the autonomous agent approach are taken as *direct* evidence in support of a particular perspective on emergence – externalism: this is the view that emergence is determined by organism-environment interactions, instead of internal processes (Clark 1995, 1997, Hendriks-Jansen 1996, Varela *et al.* 1991). However, things are not so simple, because internal representations also take a role in the implementation of autonomous agents. Like the reactive activities, certain internal representations push forward local activities which lead to global behaviour as well (e.g. Steels 1990abc). Emergence is really determined, in part, by internal processes.

Steels (1990a) criticises previous reactive systems, i.e. the implementations of behaviour-oriented agents without *internal* models/representations, on the grounds that their performance 'will always be severely limited' (p. 71). He provides two reasons for this claim. First, that external objects cannot be maintained when certain obstacles obscure the perceptual view (even if only temporarily). The autonomous agents, presumably, are incapable of maintaining external goals when they are obscured. The autonomous agents with internal models will consequently be more adaptable to environmental changes (with particular regard to the obstacles to maintaining perceptual view). Second, that autonomous agents without internal models could not maintain planning (even occasionally). They are, specifically, incapable of checking out the consequences of an action before actually carrying it out. Although they can select actions from their existing repertoire, they simply cannot plan. Hence we can infer that the implementation of internal representations (insofar as planning may promote adaptability) helps autonomous agents to improve adaptability.

Criticism of Symbolic Representations. Steels tries, accordingly, to adopt internal representations in his implementation of autonomous agents. However, he realises that he must avoid the previously discovered problems with the symbolic[14] models. He notes three. First, it is uncertain as to how enough information can be extracted from sensors in real-time. Second, there is always a degree of unpredictability in the environment, due to friction, irregularities in the objects, and small deviations of action executed by an effector. Third, an autonomous agent is always likely to encounter environmental conditions which are beyond its designers' ingenuity. As a consequence, he sees symbolic models as being 'inflexible' and 'brittle' (p. 71). The internal models he envisages, of course, must overcome such disadvantages.

2.4.4 Maes' Considerations of Exploitive Control

Maes (1995) draws attention to an unresolved tension in the work on behaviour-oriented agents, where the architectures of autonomous agents consist basically in task-driven and pragmatic solutions, in contrast to general laws and principles. As she warns when she concludes a general review of the agent approach, the agent approach may end up with an 'engineering' discipline, instead of a 'scientific' discipline (p. 158).

Scaling Problem One of the main outstanding problems of the behaviour-oriented approach is the difficulty of scaling up to larger networks. There are difficulties in action selection and the learning from experience. Such difficulties, for convenience, can be labelled the *scaling-up problem*.

Regarding the difficulty in action selection, when the architectures in question involve a larger number of (possibly time-varying) goals, be they identified implicitly or explicitly, selection between them becomes harder to achieve. It is reported by Maes (1995) that for most behaviour-oriented architectures the scal-

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[14] The term 'symbolic' is used in slightly different ways. In psychological discussions of mental representation, a pictorial imagery (just like a linguistic representation) is categorised as being symbolic representation, as opposed to distributed representation (Eysenck and Keane 1995). By contrast, in the context of Artificial Intelligence, symbolic representations are contrasted with analogical representations. Symbolic representations are shaped and connected in the form of syntax, while analogical representations are maintained by the physical nature of the representational medium, e.g. the spatial inter-relations of a map (be it printed or mental). Here, the term 'symbolic' is understood in the context of Artificial Intelligence.

ing up to larger problems is a 'disaster' (p. 150). In particular, few architectures demonstrate active perception, which she also terms 'goal-driven' perception (p. 151).

Maes identifies an attempt to solve the problem of action selection in large networks which exploits dynamical systems, as in the works of Kiss (1991), Steels (1991), and Beer (1995). Yet, as she points out, it is unclear how to explain in general emergent behaviour in such dynamical networks. This question will be addressed in the present thesis with epistemological considerations, and the focus of this thesis happens to be on active perception.

The most obvious solution to the scaling problem of action selection, as Maes (1995) points out, is to adapt the networks by evolving (as in Brooks (1992a)) or learning from experiences. However, few successes have been achieved. Indeed, Brooks does not seem to have provided detailed explanations as to *how* behaviour-oriented agents can gradually evolve into complicated organisms like primates. Regarding the difficulty of scaling-up in learning from experience, as Maes reports, the computational *complexity* of the learning systems in this approach grows increasingly so that they are no longer 'practically useful' for building complex agents when they encounter various problems in the real environment (p. 157). Some general weak points of the behaviour-oriented approach are indicated. The improvement on such weak points, presumably, would provide great facilities in the implementation of behaviour-oriented agents. As we will see in the various implementations of active perception, this is indeed the case. Among the general weak points of the behaviour-oriented approach identified by Maes, we can find three of them in connection to the limited implementations of active perception we will survey in chapters three and four.

The first weak point indicated by Maes (1995) is that few algorithms incorporate interesting attention mechanisms. This point becomes obvious once we take notice of how important the attentive control of saccades is for the smooth functionality of gaze control (see Section 3.4, page 95).

The second weakness involves the generalisation of sensor data. No algorithms, as Maes points out, exploit the structure and similarity of sensor data. Generalisation over sensor data is evidently important, as we will see in the implementations of active perception. For example, in the pursuit mechanism of gaze control, the continuity of the target object is a crucial guideline (Section 3.4.5, beginning with page 108). In addition, in the tracking mechanism, temporal continuity conditions and spatial invariance are both needed for the implementation of an Extended Kalman Filter (see Section 4.2.2, page 133, in the discussion of Dickmanns' autonomous car). However, the implementation of such continuity conditions seems unsatisfactory. Despite their importance, the above implementations of continuity are hand-crafted, in the form of '*a priori* knowledge'. It seems, so far, to remain unclear as to how such 'knowledge' can be established in real organisms.

The third weak point of the behaviour-oriented approach relates to the interaction between perception and action – a central concern of active perception research. That is, the perceptual system does not facilitate its learning of actions with newly learnt perceptual capabilities. For example, behaviour-oriented agents lack the capacity of learning what 'new features' or 'categories' of perception *need* to be created in order to facilitate the pursuit of goals in the environment (p. 157).

This problem (the third weak point) may have been hardly discussed in the implementation of behaviour-oriented agents, but active perception research is better off in this regard. This problem is taken as important in the implementation of active perception. For example, in Allen and Bajcsy (1985), the exploration of tactile processes is *initiated* to compensate for the shortcomings of visual processing in the task of surface identification (see Section D.2, page 372, and D.2). In brief, when visual processing encounters homogeneous regions where the detection of edge features or other variations is difficult, tactile exploration is initiated as additional support, with the effect of a curvature surface being eventually identified. The initiation of tactile exploration relies on a negative property – the detection of homogeneous (visual) regions. This means that the system is capable of detecting its own need for carrying out the required task.

More importantly, the system can support the need with the exploration of new features. Although the support is shaped in the form of exploration, the capability of seeking that exploration should be attributed to internal control, i.e. exploitation.

Such implemented flexibility does not seem to be the rule, however: rather, it represents an exception in the implementation of active perception. Two problems can signify the general difficulties. First, the capability of seeking further exploration, as demonstrated in Allen and Bajcsy (1985), is hand-crafted, instead of taking shape by a machinery of emergence. Second, this implementation is a flexible integration of cross-modality information, but the task (the exploration of a curved surface) is quite simple and hence can be accomplished clearly. It remains questionable as to how to identify a negative property for *every need encountered* in the real environment during the run-time processing. Such a negative property can be regarded as a goal to achieve in the later processing. Furthermore, the link between goals is also a question. Unlike the behaviour-oriented approach in general, the active perception approach saliently takes the 'need' for certain information as a central category, but it remains unclear as to how the wide range of subgoals *link cooperatively* to support the task. We will see resolutions of these two problems (of flexibility) in chapters three and four, as demonstrated by active perception systems.

To summarise, the scaling problem is a problem of increasing *complexity*: increasing complexity is quite hard to manage in the implementation of gradually larger networks of behaviour-oriented agents, due to the lack of considerations for managing both action selection and learning from experience.

Exploitation by the Planning of Goals. Apart from Steels (1990), the notion of emergence via exploitation can be supported by the planning of goals, as demonstrated by Maes (1990b). This work provides a resolution of the problem of flexibility – how to identify (as a goal) a negative property for *every need encountered* in the real environment during the run-time processing, and how the wide range of subgoals *link cooperatively* to support the task. The resolution, briefly, is grounded by the notion of *activation energy* spreading within the network of goals. Specifically, a goal is identified for later pursuit when its accumulated activation energy goes beyond its threshold. The cooperation between goals is shaped in the form of arbitration between goals which is controlled by several links (successor link, predecessor link, and inhibition link). The flow of activation energy within the network is further controlled by certain *global parameters*, such as the influence of goals (γ, see later discussion) and the influence of situations (ϕ).

In Maes (1990b), the entities to be exploited are extended to the internal representations of external world *and* explicitly represented goals. In the process of exploitation emergence can also be found, as demonstrated by Steels, but the emergence is no longer purely reactive. Instead, it is mediated by a network of differently weighted goals, out of which activation selection takes place. The action selection in such a network is subtle in that the selection itself appears to be an emergent behaviour of planning, which was dealt with in traditional AI on the basis of deliberative thinking. The emergence in Maes' implementation, however, need not be mediated by the external environment: in this respect it is like Steels (1990a) implementation but unlike Steels (1991) account (– that emergent functionality is mediated by the environment). For an account of the detailed architectures of Maes (1990b), readers can refer to the Appendix A.2 (page 347) of this thesis.

Externalism Reconsidered. Externalism, as we have discussed in a previous section, is strictly grounded on Brook's account of mobile robotics. Brooks' stance can be reconsidered in the context of ϕ vs. γ. Externalism can be characterised by the control condition that the ratio of ϕ over γ approaches infinity, where global goals have no bearing on the spreading activation-energy between action modules. According to externalism, the influence of energy spreading cannot be attributed to goals or internal representations, plainly because there is no such a thing as internal representations or (explicit) goals in Brookian robotics. There is no sense in which the global parameter γ can be understood. The impact of ϕ, the impact of external situations on the current states of the implemented robot, become exclusively influential.

Brooks' stance is actually an extreme in the research of autonomous agents. It may well be tenable in explaining emergence, insofar as the Brookian stance is applicable in the implementation of autonomous agents. As a matter of fact, that stance is an extreme in the agent approach to mobile robots. It may explain the emergence that is based on reactive (i.e. no internal representations) and non-goal-oriented agents. However, emergence can certainly be based on internal representations and goal-oriented agents, as contended by Steels (1990a) and Maes (1990b, 1995). Although externalism is popular (Clark 1997; Clark and Chalmers 1996; Hendriks-Jansen 1996; Varela *et al.* 1991; Pessoa *et al.* in press), it is grounded on an extreme. Their perspective of emergence is consequently biased by that extreme, which leads to their ignoring other possibilities of emergence.

Externalists risk ignoring other possibilities of implementation in the agent approach, e.g. internal control. In consideration of the implementations based on internal representations and goal-oriented control, i.e. exploitation, emergence is by no means purely restricted to externalism. The emergence explained on the basis of autonomous agents may, at least, equally likely be non-externalist, insofar as the non-reactive agent implementations have demonstrated.

Consider active perception research, in particular. We will see, in chapters three and four, that the exploitative control of robot activities is no less important than reactive organism-environment interactions.

Shaping Links Between *Implicit* Goals. The flow of activation-energy within a network of explicit goals is easier to understand than that within a network of implicit ones. Those explicit goals are hand-crafted, by designer, in the specification of action modules, as is illustrated in figure A.1 (page 347). By contrast, goals can be implicit in an agent system, as indicated by Maes (1995). She contends that explicit goals are easier to identify and control.

The implicit goals are not necessarily bad, however. All the flexibilities demonstrated in Maes (1990b) can be transferred to other systems with implicit goals, if we can make sense of links and the activation-energy flow within them in such systems.

Implicit Goals. Other goals of active perception implementations are implicitly expressed, in the sense that those goals (e.g. the tasks themselves) are not identified in the form of language-like representations (like those characterised in Maes (1990b)) but are instead recognised by the *performance* of perceptual mechanisms. That is, the perceptual mechanisms, by their performance, carry out certain sensory-motor or bodily-motor actions, which are not characterised in terms of competence/action modules but can still be conceived of as the goals of those mechanisms.

Note that global goals, in Maes (1990b), are explicitly specified as *actions*. In the context of active perception, *implicit* global goals of active perception can similarly *either* be shaped directly in the form of motor actions (sensory-motor or hand actions, such as saccadic movements and the hand movement for haptic perception) or alternatively take the form of perceptual information as the guidance of bodily actions.

In an analogy with Brooksian robotics, in Mataric's (1990) implementation, the sensory-motor or hand movements *per se*, regardless of their control, are driven by simple modules. Mataric's robot is supported by simple automata such as *stroll* and *avoid*, but the characterisation of such automata are not tantamount to that of the wall-following behaviour – the goal of Mataric's implementation. The goal is regarded as implicit because it is not explicitly characterised in the design but is maintained by its designer as a desired *performance*.[15] Similarly, the performance of active perception, say tracking, is supported by sensory-motor movements, such as saccades, but such movements are not tantamount to tracking – a goal of active perception.

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[15] The goals of decentralised systems are usually under deliberated control of their designers. As an example – neural network modelling, see detailed discussions in Quartz (1993).

Similar considerations hold for other implementations, such as Brooks' three-layered robot, the system of Boids, Steels' tree growth system and his rock collection robots. All such implementations have their respective goals, but they are conceived by their designers in the form of desired performance. Goals in such implementations are indeed existent, but are implicit in the design.

The perceptual guidance of bodily actions, the other form of global goal in active perception implementations, is likewise an implicit goal, because the guidance is certainly not characterised in a language-like form. Hence, except for very few cases (such as Adept, as aforementioned) we can deduce that the goals of active perception implementations are implicit.

An intriguing question regarding active perception is how implicit goals are eventually accomplished. To have a more detailed understanding than above, we must discuss the subgoals of autonomous agent implementations.

Implicit Subgoals and Factorial Conditions. Note that the subgoals in Maes (1990b) are shaped in the form of *functional conditions/descriptions* of actions. The subgoals in active perception implementations, by contrast, are not similarly shaped. The conditions of sensory-motor movements or hand movements do not necessarily take shape in the form of overt (language-like) descriptions. However, such conditions can be conceived as being alternatively shaped in the form of *factorial conditions* of (sensory-motor or hand) actions. The term 'factorial conditions' refers to the perceptual factors caught through sensors and transformed via numerical computation, such as the visual contours dealt with under a visual filter (e.g. Kalman filter – see page 119) and the features fetched in the attentive mechanism of saccades. In other words, such conditions are not functional descriptions but numerical transformations (through various perceptual mechanisms) of the perceptual features of the external world. We will have more detailed discussions of factorial conditions in chapter five (see Section 5.4, page 175), with the concept of quasi-functional and quasi-action modules.

Parametric Control in Active Perception. Now, consider the implementation of active perception. Explicit representations do not seem to suit the perceptual inputs and their transformations in perceptual mechanisms, as demonstrated by the implementations of active perception (see the detailed discussion in chapters three and four). However, the parametric control of numerical values can be preserved, because the goals and subgoals are basically expressed quantitatively, and because the influence of parameters can be found in the control parameters of dynamical systems. We will have detailed discussions in chapters five and six about the flexibility of control in the implementation of active perception.

Concluding Remark. As a concluding remark on Maes (1990b), note that the flexibility of the implemented robot performance is grounded on the *parametric control* of energy spreading, which is maintained via links. Specifically, the activation energy is distributed within the network of goals via various (to wit, successor, predecessor, and inhibition) links under the influence of global parameters (e.g. γ and ϕ) and local ones – the thresholds of action modules. Such a control maintains the exploitation of internal representations with the mediation of activation-energy, which is numerical. Compared to the parametric control, the explicit representations do not seem to be important for flexibility. The contribution of explicit representations, as considered by Maes (1995), rests on the *convenience* of identifying goals and their pre-conditions in the implementation of actions. Flexibility should be attributed to the parametric control of numerical values.

2.5 Definition of Internal Representations

For the convenience of discussions about internal representations, the term 'representations' should have a working definition, before a strict and comprehensive definition is built. The present thesis will only define *internal* representations, and leave external representations as a pre-theoretical category.

> **A Working Definition of Internal Representations:** For a cognitive system, its representations consist of a collection of single representations, each of which is a code realised at a certain level of mechanical architecture, with the conditions that such a code refers (from a third-person perspective) to something *other* than the code itself, that it causally[16] contributes to the performance of a cognitive behaviour (also in a third person's eye view), and that it connects to other codes within or across cognitive systems.

Bearing this working definition in mind will support the discussion of internal representations in this thesis.

As a note, regarding those codes that do not play a causal role in cognitive behaviour, they cannot be seen as representations as above defined. However, they can still be conceived of as representations in an another sense, e.g. the internal representations that implement an electric music keyboard.

Six Types of (Cognitive) Representations. As there exist a variety of cognitive capacities, there are different types of representation. An analysis of cognitive representations must include at least the following six senses/types:

1. **Condition-action Pairs.** The systems based on purely reactive control architectures, as indicated by Mataric (1993), are based on a collection of condition-action pairs, which are pre-fixed by designers. Such systems contain minimal internal states, maintain no internal models, and perform no search. Their performance, which consists of sensor reading and initiated actions, is consequently grounded on merely 'lookup and command', like the checking on a lookup table. Accordingly, the performance does not manifest any flexibility.

   Despite their inflexibility of performance, such systems can be seen as having certain minimal degree of internal representations built in. Because

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[16] Putting causal efficacy into the foundation of internal representations is an idea raised by Clark (1995) (see later discussions of in this thesis, Section 7.3, page 282).

condition-action pairs undeniably exist in the internal states and some people may still see the performance grounded on such pairs as cognitive behaviour, though at a very low level, those condition-action pairs can be regarded as a type of (internal) representation, in the sense that they drive cognitive behaviour. In fact, Mataric (1993) asserts that such systems 'have so little representational power ... (p. 2)'. This can be regarded as a confirmation of their being representations in a certain sense.

In the case where some people do not accept that the performance of the aforementioned systems qualifies as *cognitive* behaviour, the dispute seems simply a matter of convention as to the extension of the term 'cognitive behaviour'. Discussions about representations should avoid being trapped by the ambiguity caused by such different conventions, but had better focus on the third condition stated in the definition of representations – that representations mutually connect within or across cognitive systems. Accordingly, more important than merely contending for a yes-no answer as to *whether* certain systems have internal representations is the *role* played by the aforementioned condition-action pairs in the production of 'cognitive behaviour' and in the integration with other cognitive systems.

2. **Codes of Internal States with Within-or-Across-system Compositionality.**

An overt sense/type of representations are the codes of internal states which can be understood on grounds of the compositionality of codes in the head, without referring to organism-environment interactions.

Such representations can be further divided into two sub-types. The first sub-type of representations are explicit mental entities such as goals, purposes, beliefs, and the symbolic codes of (real or artificial) cognitive systems. It is worth noting that the fundamental components of traditional AI – knowledge representations – fall into this sub-type of representations.

The second sub-type consists of implicit procedures that can be arranged from inside a system, specifically re-organised within a domain with different orders or modified quantitatively. Representations of this sub-type are exemplified by the motor dexterity of athletes, which can be re-organised or modified by their mutual coherence, as is most salient in motor emulation. In addition, representations of such a sub-type are manifested in the pianists' dexterity beyond rote procedure, which can be re-organised or modified quantitatively by the mutual coherence of the performed musical notes.

3. **Compositional Codes of Internal States with Across-systems but Still Within-organism Integration.** The third type of representation is similar to those of the second type, but are arranged for integration *across* systems, although still from *within* organisms without recourse to organism-environment interactions. As an example, the dexterity of athletes may be re-organised or modified by the descriptive knowledge of the environment; in addition, the musical skills of pianists can be modified by emotions.

4. **Design Architectures.** The behaviours of behaviour-based agents are task-specific. Such behaviours are controlled, according to design, by certain pre-fixed architectures, such as the layer control of Brooks' three-layered robot – e.g. the automaton *avoid* and the automaton *pathplan* which implement hard-wired priority for the activities of automata at different layers. The identifiable parts of such architectures can be seen as internal representations. Note that they are pre-fixed by designers.

   Further examples are the three sub-goals of Mataric's wall-following robot – moving away from the obstacles, moving toward the boundary (the wall), and still aligned with the boundary (Mataric 1990). These three basic activities are conceived of by the designer as the sub-goals of the wall-following robot.

   In more subtle examples, the task-specific utilities of active perception are built-in representations, such as the internal forms of Snake (algorithm), the target position of navigation learning (see Section C, page 361), the heuristics implemented in the system of pursuit movements and the heuristics generally implemented in tracking systems.

Representations of this type appear trivial, because parts of a design of something S would necessarily involve certain representations related to S. Yet, this simple fact may easily be ignored, especially when Brooks (1991a) advocates intelligence without representations, which refer to representations of the second type, not those of type four.

5. **Codes that are Arranged Through Situated Activities.** Slightly more difficult to understand are representations of a behaviour-based agent which emerge in the course of organism-environment interactions, on the basis of systems' current states and current environmental circumstances. Because the contingency and unpredictability of robot states and environmental circumstances must be fully taken into account, such representations are more difficult to comprehend than those of previous four types. Environmental influences on those representations (type 5) are harder to identify than those in traditional AI, because the representations of this type are parallel and distributed in view of their causal relations to robot performance. Yet, such representations remain subject to compositionality, in the sense that different control components contribute to different aspects of global behaviour.

   For example, the energy spreading of Maes (1990b). Although the activation of energy spreading is controlled by pre-fixed thresholds over various action modules, the energy initiated by each module is spread throughout the network, as described by Mataric (1993).

   As a note, active perception systems adopt five (among others) remarkable mechanisms of code arrangement, as we will see in chapters three and four – the *energy* control in Snake, the *weight* of visual features in the attentive control of saccades, the measure of *knowledge gain* in Kalman filter, the computation of *critical variables* in the implementation of Adept (a navigating robot), and the values of *control parameters and collective variables* in dynamical systems. Such mechanisms allow the implemented systems to gain internal representations in the course of organism-environment interactions and respond flexibly.

Understanding the representations of this type is vitally important for the explanation of emergent functionality achieved by behaviour-based agents. It is not difficult to *categorise* the influences initiated by such agents as representations, but it is difficult to *comprehend* how representations of this type lead to emergent functionality, as demonstrated by various implementations of behaviour-based agents.

6. **Contingent Internal States Without Record.** One more type of internal representation may be added to the previous five types – contingent internal states which go unrecorded, such as the internal states of a thermostat. The third layer of Brooks' three-layered robot seems to fall within this category, as it does not record its influence of external factors. The representations in this type are different from those of condition-action pairs, in that those internal states may present a certain degree of integration beyond the condition-action pairs.

   Internal states of this type can be seen as representations in a very loose sense, because it is hard to conceive of any machine/device *responding* to the environment without changing its internal states to a certain degree, according to the conception of the term 'respond'.

Among these six types of internal representations, only representations of types 2 and 3 are bona fide[17] representations. While those of type 5 are arguable, those of types 1, 4 and 6 do not seem to qualify as bona fide representations.

An interesting question is the relationship between internal representations and learning. What types of representations are needed for learning, and what is consequently learnt in connection to the representations of respective types? In particular, what is the difference between reinforcement learning and constructive learning with regard to their respectively relating representations? Such questions

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[17] As an anecdote concerning the term 'bona fide representations', see its use by Clark and Chalmers (1996).

seem interesting but go beyond the scope of the present thesis. However, similar questions may arise by replacing learning with emergence. It is intriguing to distinguish between different types of emergence, which can be seen as future research. Among them, the present thesis only discusses emergence of active perception at task level.

2.6 Defining Emergence as Non-pre-determination

An important concern in the consideration of emergence is the *process* of emergence, as opposed to the product of emergence. Given this, we can further consider emergence to be an opposite concept of pre-determination. That is, a certain capacity is, and must be, achieved via emergence if it is not pre-determined; any capacity would not be regarded as emergent, if it is pre-determined. Hence we can frame the following working definition[18]:

> **Definition of Pre-determination.** Pre-determination is a process of determination for producing cognitive or biological functionality, in which the results are derivable from (and consequently mediated by) a fixed set of abstractions (in the design or the genome)[19], comprising *pre-categorised data/descriptions* of the target objects or events and pre-categorised inference mechanisms over such descriptions[20], with-

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[18] While the *notion* of pre-determination has been used in developmental studies, the following formulation is a new attempt with regard to its *definition*. Note that the present thesis is aimed at developing conceptual foundations for a particular area (active perception), as opposed to general discussions for conceptual analysis. Philosophers can further discuss whether this working definition is sufficiently adequate, for a more rigorous understanding of the defined phenomenon.

[19] This definition is aimed to cover both autonomous agent research and developmental studies. Although development does not fall within the coverage of the present thesis, this definition is not particularly tailored for the subject matter of active perception.

[20] The term pre-categorised data/descriptions means the data characterised by pre-fixed categories, such as the categories of colours, speed, and geometric shapes. The notion of pre-determination specified here, which emphasises the pre-categorised data, may help us to understand that the objectivity of Brooksian robotics is against the representations in the sense of symbolic abstractions of world conditions, as argued in Brooks (1991b). The automata in Brooks' three-layered robot do comprise internal states, which may be regarded as representations in a certain sense (e.g. physical circuits). However, what Brooks really aims to object seems to be the representations as *contents* of the external world (in theory, including the emulation of motor skills, which can be seen as the content of motor skills). What Brooks suggests, alternatively, is to initiate robotic processes directly without mediating environmental influences

out dealing with environmental influences and intra-organism processes *directly* beyond those pre-fixed categories.

The notion of pre-determination so defined may be understood intuitively in terms of the mental processes of a designer with extremely high capacity of attention which spreads wide and lasts long. The mental processes of the designer begin with contents, and the design is mediated by these mental processes. These mental processes can be analogical (i.e. not coded in language-like forms, although transferable to another working site with complete language-like codes) and yet remain pre-determined. This is because the influences of environmental factors are entirely absorbed in the mediation of data/contents.

Examples. The computational results according to orthodox computationalism are pre-determined, while the algorithms of the de-centralised approach lead to non-pre-determined outcomes. In addition, developmental traits according to nativist account of epigenesis are pre-determined. Developmental traits, such as body form, developmental procedure, or cognitive capacity, are mediated by pre-fixed categories. As a consequence, different environmental influences end up with a selection by *triggering* different pre-fixed-category traits. By contrast, developmental traits conceived under constructivism depend to *a certain degree* on organisms' interactions with the environment.

According to this definition, the determination of processes in the three main paradigms of computation at present, Orthodox Computationalism, PDP and autonomous agent research, can be made clear:

- **Determination in Orthodox Computationalism.**

  The computational result according to orthodox computationalism is pre-determined, because the environmental influences on computation must be completely mediated by the category of data of the external world.

- **Determination in PDP.**

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through the pre-fixed-category data, which are preoccupied as contents of the external world.

The algorithms of the de-centralised approach to computation, such as PDP, lead to non-pre-determined outcomes, because environmental influences are fashioned into direct initiation of computational processes without the involvement of explicit data, rather than *entirely* mediated by data before environmental factors have an impact on internal processes. Note that in PDP[21] the representations of the external world (unlike in the orthodox computationalism) are not characterised in the form of explicit (language-like) data. Before representations are presented by the nodes of the outermost layer (or the simply out*er* layer, in a three-layer network), which indicate specific contents, representations must be stored in distributed weights of connections.[22] Environmental influences are not *entirely* mediated by pre-categorised-data, because environmental factors initiate computational process (i.e. parallel distributed processing) directly. The environment begins to influence the computational processes *immediately when* the nodes of the input layer are activated. Unlike those in traditional AI, computational processes need not presume the mediation of environmental factors by pre-categorised data. Hence, environmental factors have direct influence on computational processes.

- **Determination in Autonomous Agent Research.**

  The computational processes in autonomous agent research, which is basically a de-centralised approach, are not pre-determined. It can be discussed via two cases.

  1. *Brooksian Robotics.* The computational processes in Brooksian robotics clearly need no mediation of explicit (i.e. language-like) representations, hence the implementation is not subject to the category of pre-

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[21] Unlike the suggestion raised by Fodor and Pylyshyn (1988), the PDP here is not meant as the computational mechanism that serves as the implementation of functional specification.

[22] Quartz's (1993) argument about PDP with respect to the notion innateness is not a criticism about the *processes* that are pre-determined, but about the computational *outcomes* which are envisaged in designer's mind. Hence, his criticism does not lead to the judgement of pre-determination. His criticism can be seen as a rebuttal of entirely confining computational results under design (in designer's mind). For the type of PDP implementations (of innateness) he criticises the outcome may be conceived of as pre-determined (in designer's mind), but the processes remain free from the category of pre-determination.

determination.

2. *Autonomous Agents with Internal Representations.*

   The consideration regarding pre-determination tends to be more complicated for other implementations in the autonomous agent research, i.e. those with internal representations such as Maes (1990b, 1995) and Steels (1990a, 1991), to mention only a few. Representations are formed earlier than the processing over them. However, direct environmental influences remain on the computational mechanisms, because the influence of the environment does not end up with the availability of internal representations (types 2 and 3) but also serves to determine various degrees of activation on the control processes, such as the energy spreading in Maes (1990b) and the interactions between geological agents in Steels (1990a).

Pre-determination is a Matter of Degree. The role of pre-determination in development seems to be a matter of degree. Certain traits are pre-determined while others are not. Environmental influences in many cases are further subject to maturation windows, i.e. specific time periods when organism-environment interactions take effect significantly. To see it from another angle, the environmental influence on emergent functionality (e.g. biological functions or psychological capacities) is a matter of degree.

A Pervasive Origin in Emergence. According to this notion of emergence, it is easy to claim that everything pertaining to real organisms must be emergent if its ontogeny is not completely determined in genes. A stronger claim can be made for the phylogeny: everything of real organisms must be oriented in emergence, given that it is not created in its phylogenic origin.

Modelling of AI is a little bit more complicated, given that it is necessarily a work of design but not everything can be pre-determined in the design. In particular, the design of an autonomous agent must be seen as a ground for the emergence of *global* behaviours, which by conception are not pre-determined in the design.

Conceiving Emergence as Global Behaviour. When certain behaviours are regarded as global behaviours, they are conceived of as something beyond the design. Hence, it is straightforward to see global behaviours and emergent behaviours as being conceptually identical. For example, when Forrest (1991) states that global behaviours are side effects of local instructions, he addresses (by conception) behaviours at different levels (i.e. local and global). In contrast, it is arguable (as an empirical issue) whether certain phenomena/traits can be appropriately regarded as being achieved from global behaviours.

Judgement of Pre-determination is an Empirical Issue. It is an empirical issue whether a single particular behaviour, or trait, is pre-determined or not. For example, in developmental psychology, there are often disputes regarding whether a particular capacity is innate – i.e. pre-determined in the course of development. While constructivists disagree, selectionists (e.g. Gazzaniga (1992)) see developed capacities as innate in the course of epigenesis (as opposed to the pre-formation in the germ line.). That is, such capacities are pre-determined but only appear in the process of maturation. This is an empirical issue, rather than purely a matter of conceptual analysis regarding the meanings of innateness, construction, development, etc.

In brief, the distinction between global and local behaviours *means* the conceptual difference between emergence and pre-determination, while seeing certain traits as resulting from global behaviours (but not derived from local instructions) is an *empirical judgement.*

2.7 About the Working Definition of Active Perception

A More Comprehensive Conception of Active Perception for Future Research – Extending from Sensory-motor and Bodily Actions to Attention. On the above account, selection of sensory-motor or bodily actions is a necessary condition for active perception. Such a sense of *active* perception is not entirely intuitive, because a perceptual system that works out the needed perceptual information (for required tasks) and directs their attention toward the collected perceptual inputs without driving their (sensory-motor or bodily) actions would not be counted as a case of active perception. Yet, perceptual systems with such a capability of attention selection seem to qualify as active perception systems. For example, when humans stand still, think about the most relevant acoustic inputs for the interesting information (e.g. the sound of Snake moving in the grass), and pay attention to the most relevant acoustic information as they hear, the working acoustic capacity seems to be active.

As a consequence, the above stated meaning of active perception is not sufficiently comprehensive, but has its emphasis: observers participate in the environment by sensory-motor or bodily actions. This is a matter of limitation upon the research paradigm/methodology of the present active perception systems, which advocates the notion of active perception on the basis of mobile robotics, by implementing moving perceptual systems (such as computer sensors located on an movable arm or robot body). Internal processes serve to drive the sensors to the most relevant *positions* in the environment or to provide guidance of *bodily* actions, such as navigation and grasping. By contrast, the above active perception on account of attention certainly goes beyond this research paradigm. Readers must bear in mind that the above meaning of active perception pertains to the current research paradigm of mobile robotics.

Restricting the meaning (conception) of active perception has its negative and positive sides. On the negative side, the resulting conception of active perception is *less comprehensive* than the intuitive one, which is derived from considering all subtle capacities of organisms in the real world. On the positive side, the restricted meaning is *easier to examine* by experiments (i.e. various robotic implementations) and has a *focus of explanation* regarding what makes active perception systems perform satisfactorily in the real environment. As a balance between the negative and positive sides, relativising the notion of active perception to a research paradigm remains a good choice.

There are two reasons for this. First, the understanding of active perception is not simply a matter of conceptual sophistication (including comprehensibility); rather, the successful *implementation* of active perception systems is much more important. Without *successful* implementation of *various* active perception systems there cannot be a beginning of explanation as to what makes active perception work well. Second, research on active perception can be gradually extended to different research paradigms, grounded on which the previous conception and explanation of active perception can be compared with and consequently be extended. The understanding of active perception would then be likely to improve firmly and steadily. The present thesis will follow the above restricted meaning of active perception, and its extension can be left for a further research.

Extending from Bodily Actions to All Behaviours. Intuitively, the maintenance of nearly all bodily actions in the environment needs the support of active perception, primarily vision. Such an intuitive notion can be found in active perception research, as a branch of autonomous agent research. For example, car driving, hunting a bird and catching a ball are all supported by visual tracking. Navigation is supported by saccadic movements (in order to understand the visual scene) and the planning of visual tasks (for the understanding of the spatial relations between obstacles and the target).

Active perception *can* be regarded as a particular case of *active behaviour*, which is an extended stance posed by certain researchers in active perception. According to Colin Johnson (1996), certain researchers in active perception 'base their work on the notion, that *everything humans do* – learning, cognition, perception, recognition, etc. – is dependent on the performance of certain active behaviors in a certain order' (abstract, C. Johnson 1996; italic added). However, the main trend of active perception research does not discuss all human behaviour, but remains limited to the relatively conservative notion, that *bodily actions* are dependent on the performance of active perception. Given the limited space available in a thesis, the present thesis also focuses on this conservative notion.

Active vs. Passive Perception. The aforementioned processes qualify perception as active, as opposed to passive, on the grounds that those processes enable the *observers* (organisms or robots) to take certain *selected actions* to contact different aspects of the *environment*. In other words, those processes enable perception to be *active*, in the sense that the perceptual systems have a certain degree of freedom in the selection of processes over perceptual inputs or their internal transformations in the observer-environment relationship, in favour of the accomplishment of the required perceptual tasks. Here, the concept of freedom does not presume some non-mechanistic vital force managing selection (as in the notion of a homunculus); it means, rather, the possibility of maintaining selection over perceptual inputs or their internal transformations, as opposed to the pre-determined[23] processes needed for fully elaborated recovery of perceptual content.

In such a sense, the term 'active perception' is meant as a *faculty* of organisms, or of artificial systems, which consists of active perceptual processes. Although it is conceptually possible that certain perceptual processes do not serve to enable active perception (as a faculty), those processes will not make perception be passive, given that there exist certain other processes that enable active perception, as supported by neuroethological findings (mainly on gaze control and tracking, see discussions in chapter three). In other words, the fact that perception is enabled as active by certain processes is a *sufficient* condition for active perception. This understanding of active perception can be seen as pro-

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[23] For understanding the notion of pre-determination, please refer to Section 2.6, page 64).

viding a definition of active perception (on the basis of the research paradigm of mobile robotics), as seen in chapter 1 (see Section 1.2.1, page 3).

According to this definition, the visual system implemented on the basis of Marr's vision theory is not active, because the observer is stationary and hence has no freedom for selection over perceptual processes as above required. Systems on the basis of Marr's vision theory can consequently be termed *passive* systems. That is, the concept of being passive is the negative counterpart to the concept of being active.

***Active* Perception and Emergence.** The aforementioned definition of active perception does not exclude symbolic systems from the possibilities of *active* perception. Yet, this does not mean that a symbolic active perception system would consequently exhibit *emergent* behaviour, although the active perception systems studied in the present thesis do so. The emergent phenomena studied in the present thesis happen specifically in behaviour-based systems, but are not necessarily seen in *all possible* active perception systems. Symbolic systems can exhibit emergent behaviours, as in part conceived of in Cariani's (1991) thesis of emergence and demonstrated by Ray (1991), although the emergence of this type seems to be different from the type of emergence at issue in the present thesis.

Note that emergence seems to be a group term referring to various types of emergent phenomena. The present thesis only addresses the task-level emergence presented in the current active perception systems, which are behaviour-based systems. The notion of emergence as non-pre-determination, which is introduced in this thesis, may not suit all possible emergent phenomena. Indeed, it would be inappropriate to expect to arrive at an all-inclusive definition of emergence simply by studying limited types of emergent phenomenon. What we can see about emergence in the present thesis is a definition of emergence particularly tailored to suit the current active perception systems. In future research, such a definition may be extended or modified to suit more types of emergence, by considering *other* kinds of emergent phenomena.

Various Degrees of Active Perception. Although the existence of an active process suffices to qualify a perception system as active, *whether* a perceptual system is active may not be so important as *how* it is active. That is, the property of being active is not a matter of yes-and-no, but comes in degrees. Adopting a variety of useful active processes confers a high degree of this property (active perception), and so would facilitate a perceptual system to perform well in the environment.

It is worth noting that understandings of active perception, however a high degree of being active an active perception system may be, must not be so radical as to abolish the necessity to *recover* the external world, from the *collected* perceptual inputs. What active perception research argues against is the *full* recovery of perceptual inputs; yet, no recovery no perception (see discussions in Sections 7.5.2 and 5.4.1, page 311 and 177). The issue raised by active perception research is to maintain selective collection of perceptual inputs and partial recovery of the gathered information, as a reminder before we proceed to survey various architectures of active perception systems.

Posing an extreme position may be easy. However, in the light of explaining the unity of cognitive phenomena – a main goal of this thesis – what indeed needs deliberations is where to stand in the middle ground, to put it metaphorically. In this light, various theoretical stances need to be tackled together in the middle ground.

2.8 Summary

The discussion of background considerations centres around three topics – organisms' adaptability to environmental factors, the internal control of behaviour-based systems, and the definitions of three regularly used terms. For these three topics, this chapter provides conceptual analyses, discussions of the various design strategies of behaviour-based systems, and discussions of a current account of emergence (Steels' thesis of emergent functionality).

Certain important conceptions relevant to the explanation of emergence and active perception are discussed. First, the notion of autonomy is analysed in relation to the notion of adaptability, and it is established that the primary meaning of autonomy is self-maintenance for presenting high adaptability to environmental circumstances.

Second, the notion of emergence is defined as a negative concept of predetermination, which is defined in turn as *pre-categorised* data/descriptions and inference mechanisms.

Moreover, for the understanding of organism-environment interactions, discussions in this chapter also address the role of ecological niche, in order to explain the relationship between organisms and the environment, in particular the grounding of internal representations.

Last, the concept of *internal representations* is analysed into five types, in order to identify clearly the various types of representations implemented in active perception systems. An advantage of analysing those types can be seen in understanding the integration of representations across types. As an example, the emergent functionality of gaze control relies on the integration between the heuristic knowledge of visual events (type 3), the different mechanisms of pursuit movement and attentive control of saccades (type 4), the weight comparison between visual features (type 5), and the computation of overshoot distance for pursuit movement (type 5).

For distinguishing between various design strategies of active perception systems, two issues are discussed. The first is the basis of behaviour-based system on Brooks' subsumption architectures and the advance of internal control on account of Steels' exploitative control and the action modules which are exemplified by Maes' control of energy spreading. The second issue is the relationship between exploration and exploitation, which are two generally undertaken control strategies for implementing behaviour-based systems. Exploration emphasises robots' directions in different parts of the environment, while exploitation emphasises the planning of robot actions based on heuristic knowledge of external events and the computation of certain variables and their inter-connections, such as energy spreading (Maes (1990b)), and the differential equations maintained by dynamical systems.

Discussions on Steels' account of emergent functionality argue that this account leaves the emergent behaviours of behaviour-based systems largely unexplained. In this regard, discussions in this thesis will provide several explanations of emergent behaviours, with a focus on active perception systems.

Part II

A Case Study

Chapter 3

The Nature of Active Perception

In the following two chapters we will review active perception research, by discussing its main achievements with regard to the various types of mechanisms. The purpose of this review is to answer the aforementioned question concerning activeness: what makes active perception work. What makes this topic interesting is that active perception systems are *autonomous* systems which work under *real-time* constraints but respond well to the *real environment*, which is somewhat unpredictable.

In this chapter we discuss the nature of active perception. The notion of active perception we discuss is generalised from the notion of active *vision*. So far, the study of active vision, in respects both of the scientific exploration of evidence and the accompanying theorising, remains in its infancy (Churchland *et al.* 1994), let alone its generalisation to other perceptual modalities, or even to cross-modality systems. However, the implementations of active perception we will discuss are not limited to visual modality. This point is supported by discussions on cross-modality systems, which are listed in Appendix D. With that point being supported, although the following discussions are based on implementations of visual systems, the characterisations of active perception are not limited to a single modality.

Such a move, from vision to perception generally, would help to extend the research of active properties from vision to other perceptual modalities, with two ways. One, perceptual judgements are facilitated by the integration of perceptual information across modalities (Churchland *et al.* 1994; Allen and Bajcsy 1985; Scheier and Lambrinos 1996). Two, non-visual modalities not only stand in a position to support visual processing, but stand on their own as being active. One piece of evidence of the active perception with a non-visual modality is the selective attention in the processing of *acoustic* information (Cherry 1953). The system of attention *directs* the resources of acoustic processing to certain acoustic cues needed for the required tasks, with the effect of active hearing. Following this line of argument, in our discussion we will see the evidence supporting active vision also as evidence in support of active perception. Of course, there might be differences between modalities, regarding the strategies of active processing in respective modalities. Our discussion will at least provide several hypotheses for future research with regard to non-visual modalities. Such hypotheses will remain subject to falsification in the future, but at present they would tend to be plausible insofar as they are manifested in the evidence supporting active *vision.*

3.1 The Traditional Perspective on Vision

The computer implementation of mammalian vision was traditionally lead by Marr (1982), who initiated the study of vision under the notion of computation, which can be outlined in terms of the following two assumptions:

1. Visual Processing as Full Scene Recovery. Visual experience consists in a *fully elaborated* representation of the visual scene, with the visual representation *corresponding to* that visual scene. Visual processing serves to *recover* such a fully elaborated 3-D (three-dimensional) representation with regard to various visual properties such as depth, colour, contour, position, size, motion, velocity, etc., from the 2-D (two-dimensional) retinotopic maps (Tsotsos 1987; Charniak and McDermott 1985). Eventually, visual processing ends up with a reconstruction of the visual scene *in* the brain/mind (Churchland *et al.* 1994).

Being a fully elaborated representation, the internal counterpart of a visual scene is not a partial representation with limited emphases. Whatever visual tasks are required, there is no selection over different parts of the fixed visual scene and no difference in emphasis between the selected parts. In addition, being a *correspondence* to the visual scene, visual experience serves to provide a *description* (although possibly with certain interpretations)[1] of the external world, with a neutral stance as to how much certain visual features contribute to bodily (motor) actions, and in turn how important certain activities of visual detection are for survival. In this vein, visual processing is taken to be capable of standing on its own as a set of independent modules without reference to anything about motor activities, or to their contributions to survival.

2. Visual Processing is Hierarchical and Bottom-up. Visual processing is supposed to proceed from the already available retinotopic maps, then to the lateral geniculate nucleus (LGN), and eventually to a hierarchy of visual modules implemented in various cortical areas, as manifested in cognitive neuroscience (Van Essen and Anderson 1990). Among such modules of visual processing, higher level processes receive inputs from the outputs of lower level ones, out of those inputs such higher level processes *extract* specific visual features. This is a *complete* sequence of visual processing. There is no need, then, for precedent motor activities that strive selectively to make available *relevant* visual features, nor does it need intermediate activities that serve to *fetch* perceptual information in support of the interpretation of features in the occurrent visual processing. Visual processing, basically, is understood as being a *passive* activity of data extraction. Even if there is a need for the interpretation of visual information[2], the visual sub-systems only extract features and do inferences on the basis of the *already available* information. They would not make an 'explanatory' or 'predictive' inquiry over circumstances of the external world, in relation to the required visual tasks (Churchland *et al.* 1994, p. 26).

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[1] A venerable epistemological issue is the intrinsic relationship between description and interpretation. In the present thesis, there is no space to launch discussions about this topic in detail.

[2] Note that Marr (1982) supposes visual computation to be an activity of inference.

Along with the *sequence* of visual processes, visual processing basically consists in the extraction of increasingly specific visual features. There is no need to *explore selectively* a variety of areas in the target scene, nor do we need to filter them out with regard to their relative importance supporting in the required visual tasks. In this way, visual processing follows strictly the above bottom-up orientation in support of a hierarchical sequence of visual processes, from early, via intermediate, to high level processing. There is no possibility of re-organising the order of the above sequence in order to make available certain information in response to the *inquiry* issued by the visual sub-systems. The perspective of passive computation would not consider the features of the visual scene which are not yet available but remain important for the completion of the required tasks. In particular, there is no need to make clearer certain features which are crucial for survival, e.g. whether the shape and velocity of certain shading signal the approaching of the predator.

Visual processing is regarded as an activity of passive extraction of the available information, without the need to maintain sensory-motor activities in order to address selected features in the environment. This is because the information received in the retinotopic maps is deemed as being sufficient for perceptual understanding. Perception need not identify certain goals and thereby pursue relevant perceptual features; rather, it simply receives whatever is available in the perceptual receptors. There would not be any *arrangement* in the visual systems for further activities that serve to fetch whatever is *still* needed for prediction or explanation about circumstances of the external world.

3.2 The Rise of Active Perception Research

That vision is active is first advocated by Aloimonos *et al.* (1988), Bajcsy (1988), Ballard (1991) and Ballard *et al.* (1993), in the study of mobile robotics. The general idea is that the processing of visual information is not passive but active. That is, visual processing is not a reconstruction of visual properties from the retinotopic-map which receives visual inputs passively, but is an *exploitation* of sensory-motor processes with the effect of simplifying visual complexity and facilitating further perceptual processes, in order to generate visual guidance in support of certain bodily movements.

In this section we discuss the characteristics of active vision. Bear in mind, such characteristics are not limited to visual modality.

The Relationship between Active and Passive Vision. A landmark in the departure of active perception research from the traditional perspective of visual processing is the shift of the beginning point of visual processing, from the reconstruction of retinoceptive maps (as Marr (1982) puts it) to an earlier visual stage – gaze control. Note that gaze control is not simply supported by oculomotor systems, although there appears to be a direct analogue between the two terms 'gaze-control' and 'oculo-motor systems'. Specifically, gaze control relates more widely to bodily movements, and is mediated by central neural systems, specifically the LGN and a variety of cortical areas. This landmark implies that vision is *both* active and passive, if we see the traditional perspective of visual processing as being characterised by the reconstruction of retinotopic maps and consequently redefine the reconstructed visual information as *non-active vision*.

The relation between active and passive vision can be encapsulated in Kantian terms: active vision without non-active processing is empty while non-active vision without the complement of active vision is blind.[3] Such a relation provides a way of bootstrapping the relation between active and non-active vision: non-active vision relates to the elaboration of *already available* retinotopic maps into abundant visual experiences and the accompanying processes, while active vision neatly serves to *make available* (with the support of gaze control) 'sufficient' retinotopic maps that are required for the visual processing of certain required tasks. The collection of retinotopic maps would be sufficient if only the elaborated visual processes could provide *enough*, or a little more surpassed, information for

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[3] In Kant's Critique of pure reason, *blind* is used in the context of unguided activities. Here in the present thesis, the term 'blind' does not really imply that *nothing* is detected, but that there is a lack of well-structured *guidance*.

the *further* processing of motor actions and[4] visual recognition. Thus a central claim of the active vision perspective is that visual processing does not lead to a *fully* elaborated *image* of the external world but only serves to provide relevant information for further *use*.[5]

3.2.1 Two Perspectives of Active Perception – AB and BC

Two Senses Provided by Brooks. The distinction between the following two perspectives of active perception can be seen as originating from, but further specifying, the two senses that Rodney Brooks singles out in the Forward to the book *Active Vision*, edited by Blake and Yuille (1992), as the central features of active vision (the active perception with regard to the visual modality):

- **(AB)** 'active *operation in the world* in order to change the images that are being *collected* in a way which enhances task achievement' (italics added),
- **(BC)** 'active autonomous processes (e.g. snakes)[6] which exploit the *coherence* of images in a sequence in order to *efficiently* and *reliably* track aspects of interest over time' (italics added).

The AB perspective/sense of active perception (vision) emphasises the sensory-motor or even bodily activities that serve to collect (or make available) perceptual images (e.g. retinotopic maps) and change them. By contrast, the BC perspective/sense of active perception emphasises the internal autonomous processes that serve to bring about (not hierarchically extract) coherence in per-

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[4] Motor actions may happen *after* visual recognition, as mediated by overall planning. However, motor actions can also happen *before* visual recognition, as is evident in sensory-motor coordination.

[5] As we have stated, the *use* may go beyond the scope of vision, such as varying bodily actions, which are not limited to oculomotor control or sensory-motor coordination. This point is not made clear in Churchland *et al.* (1994), who conclude their discussion of active vision with the following statement: 'visual systems evolved ... *because* visual perception can serve motor control, and motor control can serve vision to better serve motor control, and so on' (p. 59; italics added). At this point, they seem to have left out the contribution of visual information in bodily actions, such as running *faster* to catch a bus, which do not serve *vision* to better serve motor control. As a result, it is hard to say that the functionality of vision can be supported by the bodily movements such as foraging, fighting and fleeing.

[6] There may be many instances of Snake, a computational algorithm for tracking external (visual) targets (see detailed discussions in Section 4.1.1, page 114).

ceptual outputs that facilitate the efficiency or effectiveness/reliability of perceptual processing. As a note, the notion of internal cohesion, that we will introduce in chapter six (Section 6.4.1, page 242), hinges on Brooks' terms 'coherence' and 'reliably'. In the present thesis we will provide further exposition of active perception, going somewhat beyond the ideas in Brooksian robotics.

There are, so far, no generally agreed characteristics of active vision. Nonetheless, certain central properties of active vision can be discerned from the ideas emphasised in the study of active vision, as seen in the following three groups of points[7].

3.2.2 Commonalities Between Two Perspectives

(O1) Relevant Points of Processing in support of Visual Explanation and Prediction. As a tenet of active perception research, visual processing does *not* elaborate *fully* a visual scene of the external world. Only relevant aspects to the *required tasks* will be explored. The relevance to a required task can be manifested in the travelling path and visited areas of foveation, which is supported by a variety of visual subsystems. The visual systems visit and revisit interesting points depending on the speciality of the required tasks (Yarbus 1967). Agents may be entirely driven by autonomous visual sub-systems and consequently be attracted passively; alternatively, they can maintain attention on certain points intentionally. The number of visits to points in a scene is subject to the complexity of the tasks and the agents' familiarity with the task. What is intriguing is that the path of foveation manifests how the foveating sub-system, which is an *autonomous* system, seemly 'strives' to 'make available' the required visual information. It is an epistemological question how such a seemingly intentional activity is made possible in an autonomous system.

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[7] In these three groups of points, group AB signals the points emphasised more in the spontaneous motives of behaviour-based vision, group BC relates to those emphasised more in interactive vision. The term 'AB' is a mnemonic for the perspective raised by **A**loimonos *et al.* (1988), and **B**allard (1991). The term 'BC' is a mnemonic for the perspective advocated by **B**ajcsy (1988) and **C**hurchland *et al.* (1994)). By contrast, the group 'O' signifies the points commonly emphasised in both these two approaches to active vision

Although they are autonomous, such visual sub-systems are by no means neat modules. They interact with the aim of explaining the circumstances of the external world or more effectively predicting those circumstances. They do so by foveating and re-foveating important points within the visual modality, and by fetching perceptual information across modalities for the integration of perceptual information across time (Churchland *et al.* 1994, p. 26). The visual scene is consequently made more and more vivid, in response to the required tasks.

(O2) Passive Sensors Employed in an Active Fashion Active perception is not active on account of active *sensors*, which transmit certain electromagnetic radiation (such as radar, sonar, ultrasound, microwaves) into the environment in order to measure the reflected signals (Bajcsy 1988; Ballard 1991). Perception is active due to the observers' activities. At this point, however, the AB and BC perspectives have different emphases, as Bajcsy (1988) suggests.

3.2.3 The AB Perspective

(AB1) *More* Processes Making the Computation Simpler. The AB perspective emphasises the strategy of exploration, that the exploration of *more* processes may turn out to make the computation simpler and quicker, if those processes bring about needed information for the required task (Aloimonos *et al.* 1988; Ballard 1991).

(AB2) Adopting Exocentric Coordinate Frames by the Binocular Vergence System. Active vision systems can adopt *exocentric* coordinate frames (with gaze control), instead of being confined to an *egocentric* coordinate frame (i.e. viewer-centred frame). The advantage of adopting those exocentric coordinate frames is a significant reduction of complexity in the computation of visual information. For example, the adoption of some object-centred frames helps an observer to exploit details of certain objects. Furthermore, the adoption of a world-centred frame[8], by manipulating gaze control to keep fixating on the centre of the frame, helps the observer to exploit the mutual relations of aforementioned object-centred details. Furthermore, the fixation of a certain exocentric coordinate frame circumscribes[9] the oculomotor control on that particular frame, keeping everything in it invariant when the observer moves. Thereby, such an exocentric coordinate frame simplifies the oculomotor processes locally, regardless of their relation to the egocentric coordinate frame (Ballard 1991).

(AB3) Implementing Task-specific Modules. Aloimonos (1993) re-affirms the importance for active perception research to take advantage of an essential computational strategy of autonomous agent research – implementing *task-specific* modules, as opposed to general-purpose modules (such as those in Marr's visual systems). When such a consideration is combined with (AB1), it can be inferred that the needed information for simpler and quicker computation (in support of a perceptual task) must be made available by task-specific modules.

(AB4) Accessing Only the Important Aspects of the Visual Field by the Oculomotor Activities of Foveation. Active vision systems can avoid blind search by *accessing* only the important aspects of visual field in support of the visual tasks. Such systems can *move* their visual organs (or cameras) closer to objects by bodily movements, and such systems can further access the important aspects of envisaged targets by gaze control. Specifically, they can change focus by their vergence systems, drive the fovea of retina to specific features by saccadic movements, shift fovea elsewhere to alternatively maintain pursuit movements on the already foveated target when the target or/and the observer is moving. What is more, the vergence, saccades, and pursuit, are all self-generated within the active vision systems. Every exploited feature, thus, can be seen as an *addi-*

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[8] Strictly speaking, the fixation on the centre of a visual *scene* does not lead to the fixation on the centre of the 'world', although Ballard adopts the term 'world-centred frame'. A more appropriate term may be '*event*-centred frame'. Even though the visual agents are moving and the world circumstances are changing, the agents' fixation on a certain object of an *event* would help to exploit that event. Thus, the visual fixation generates an event-centred frame.

[9] It is circumscribed by the active vision systems with certain computational processes. For example, the circumscription can be achieved by limiting the computational processes on the region of near zero disparity produced by a binocular vergence system (Ballard 1991).

tional constraint on visual processing, which facilitates computational processes significantly (Ballard 1991).

(AB5) The Computation of Known Parameters Provides Constraints in the Computation of Unknown Parameters. Aloimonos *et al.* (1988) assert that visual computation is not based on the correspondence of micro-features, unlike the traditional vision theory. Rather, by observers' movements *the computation of known parameters* will provide constraints for computing *unknown* parameters. Specifically, a moving visual system may take advantage of powerful constraints derived from the local transformation of certain parameters. Thus, when visual stimuli are rich but the known parametrization is only partially available, computation taking advantage of such constraints would be powerful. To see it from a different angle, certain visual constraints are derived from the computation of known parameters, i.e. from the explorative activities themselves.

3.2.4 The BC Perspective

(BC1) 'Purposeful' and 'Explanatory' Control. By contrast, the BC perspective emphasises the strategy of control, that the control process of perception is made adaptive to the unpredictable environment by the goal of the required task and the various feedback information which comprises the top-down (i.e. 'global') information and the interactions between bottom-up (i.e. 'local') processes (Bajcsy (1988), pp. 9-17). Such control is expected to facilitate the judgement of most likely results under uncertainty. In terms of Bajcsy (1988), the strategy of active perception is that the perceptual organs adjust '*purposefully*' in order to make their activities 'explanatory, probing, searching' (Bajcsy 1988, p. 1; italic added).[10]

Such terms need reconsideration from an epistemological perspective, because they seem to presume autonomous systems to be not only intentional but

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[10] Such a notion can be found in Blake *et al.* (1992) (See Section 8, page 129).

also prudent. Such a presumption does not seem to be well grounded, for it cannot be taken for granted, yet seems hard to explain.

(BC2) Perceptual Cues. Intrinsic to perceptual systems is the '*rationale*' of bodily actions, which guides organisms to act such that they take advantage of environmental cues, or react to specific environmental challenges swiftly. Perception does *not* end up with *pure descriptions* of the external world. Instead, it provides a variety of heuristics that help organisms survive well in their activities of feeding, fleeing, travelling, fighting, or reproduction (Churchland *et al.* 1994, p. 25)[11].

For example, optical flow, as Gibson (1979) points out, provides *explicit* guidance for flying in the form of 'affordance', by manifesting direction and relative speed. There are even cues for further actions. *Insofar as such perceptual heuristics are available*[12], organisms need not achieve guidance by the computation of internal representations. Because further computation is waived, bodily activities on the basis of such heuristics tend to be swift, as in the fleeing reaction initiated when prey detect certain apparent cues of their predator's approach, such as an eagle cue manifested in the form of certain conformation of visual shades and shapes. Those cues are by no means descriptions of the predator's approach, but serve as *signals* of such an event. Such an ability of organisms seems to be cast in the form of instinct, which is, of course, determined in the course of evolution and is in-built in ontogeny.

By contrast, some heuristics can be established by learning. After frequent encounters, the brain may eventually learn that certain patterns *typically* go

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[11] The point of exploiting environmental cues is widely adopted in the behaviour-based *implementation* of active perception systems, as seen in tracking systems and the implementation of pursuit movements. Yet, this point is hardly stated in *theoretical* discussions of the behaviour-based implementation of active perception systems; rather, it is stated by cognitive neuroscientists – Churchland *et al.* (1994) – in their summary of active perception research initiated in mobile robotics. Hence, the credit of identifying this theoretical point must be attributed to Churchland *et al.* (1994)

[12] Gibson does not cast this caveat. He denies utterly the need for computation. Abundant evidence in cognitive neuroscience, however, serves to challenge such a claim (see Kandel *et al.* 1993, 1995). Despite such evidence, Churchland *et al.* (1994), who are three cognitive neuroscientists, re-affirm the utility of optical flow in providing cues for navigation, with regard to speed of the navigator and distance of objects (see Churchland *et al.* 1994, pp. 51-52).

together and accordingly the number of iterations in the information flow can be significantly reduced (Sejnowski 1986). The quick response to letters and words in humans, as Churchland *et al.* (1994) suspect, may be subject to this type of learning, which they term 'overlearning' because of *frequent* encounters (p. 51).

As we will see in chapters five and six (see Section 6.5.1, page 255), the above perceptual cues of a certain species (which are non-descriptive but are clearly available in most cases[13]) manifest implicitly the particular conditions of its ecological niche. The swift fleeing (i.e. the quick running away of a prey), for example, manifests the need to escape from the chase of a certain predator. The optical flow which guides flying reveals the ecological niche of a flying species and the importance of that guidance for their survival in their particular niche.

It should also be noted that the aforementioned cues are *available* (in-built) for use (fleeing, judging the distance, etc.), which are different from the computational economies brought about by motor activities (e.g. bodily movements, or the vergence and saccades of sensory organs). As previously discussed in (1b) (see Introduction 1.2.1, page 4), those movements serve to *make available* the visual representations needed for completing the required tasks. The computation of internal representations is still required, even if it is not needed in the circumstances of aforementioned cues.

It also needs to be noted that evolution might provide available perceptual cues implicitly. This point is manifested in various visual illusions, such as the illusion Ames' Room. The adult looks smaller than the child when the child stands on the shorter side of a non-square room. Every corner of room is perceived as rectangular, but no *single* cues actually correspond to the representation of a rectangle. It is a *global* effect of a 'room', established as a built-in capacity by evolution and consequently is presumed in our experiences. In a similar illusion, the concave areas of a baseball look convex when the picture of the ball is put upside down, and this is because the light source is presumed as being *above*, as we evolved to take advantage of the fact that sun appears this way in the

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[13] It remains unclear as to whether the above over-learnt reading skills are available explicitly.

environment. Each presumption, plausibly, manifests a certain aspect of the human ecological niche.

(BC3) Integration of Perceptual Processes. The perspective of interactive vision presents a sharp alternative to the traditional (i.e. bottom-up and hierarchical) perspective of perceptual processing, not only because of the above *active* properties, but also on the basis of the *integral* connections of real neural networks, in contrast to cortical modules. Such connections are evident in both neurophysiology and psychology. On the neurophysiological side, such integral connections are manifested in recurrent networks: the thalamic-cortical feedback loops, and the concurrent brain waves functioning across cortical areas. On the psychological side, the integral connections can be seen in the integration of various cognitive information (Inui 1996; Inui and McClelland 1996). Such evidence strongly suggests the opposite of the bottom-up and hierarchical perspective of perceptual processing.

Experiences stored in memory may affect perceptual judgement (Churchland *et al.* 1994). The integration of visual information with perceptual information from other modalities may improve perceptual judgement significantly. Hence, the massive interactions across cognitive modules (or across cortical areas) must not be overlooked. They are likely to support the effective processing of perceptual information which may previously have been entangled to various degrees.

This is in particular true for reinforcement learning in cross-modal tasks. The number of processes that are involved in cross-modal tasks may be *firstly* reduced by the perceptual emphasis on relevant points discussed previously in (O1) and (AB4). The learning tasks may be accordingly simplified significantly (Churchland *et al.* 1994, p. 54; Whitehead and Ballard 1990). However, the reduced emphases may remain entangled across modalities. Without the processing carried out *later* by the networks across modules (or brain areas), it would be hard to disentangle the multi-modal perceptual information, and consequently organisms' response in real-time, which is required for survival, would not be feasible. This point is evident in sensory-motor coordination, for the organisms generate lots of cross-modal associations, which would reduce the high-dimensionality of the high-dimensional sensory-motor space and consequently facilitate learning across modalities when organisms move (Pfeifer and Scheier 1997). Categorisation may also be facilitated by the proprioceptive cues generated during the real-time cross-modal activities (Scheier and Lambrinos 1996). Thus, integration of information may facilitate real-time learning, actions and the reactions learnt on the basis of cross-modal associations.

An Epistemological Exposition of 'Explanatory' Sensory-motor Movements. The aforementioned notion of 'explanatory, probing, searching activities of sensory organs', which is raised by Bajcsy, is not entirely inadequate, although hardly straightforward to describe autonomous agents (i.e. behaviour-based systems). This notion can be better explained in our discussions of active perception researches. The notion of purposefulness[14] can be understood as being manifested in the *selective* (over inputs data, computational processes, and even algorithms) and *exploratory* (with regard to the critical aspects of the required task) activities, that facilitate the computation needed for accomplishing the required task. It is easy to realise that such activities *look as if* they have certain built-in purposes that *serve to drive* the selective and exploratory activities.

A goal derived from a required task (at the time-scale of task execution), e.g. keeping the car on the right track without crashing, can serve to *constrain* the processes of autonomous systems, in the sense that the accomplishment of such a goal is *facilitated* by a variety of *connections* between various mechanisms of the autonomous systems, as will be made clear in the notion of intermediate conformation. That goal does not serve as a purpose envisaged by the autonomous systems, but as an *adaptive outcome* which originally emerges in the course of evolution through gradual adaptations to the ecological niche, as we will have

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[14] The adoption of intentional terms is not unusual in the active perception research. In particular, the notion of purposefulness seems to have been adopted as a background understanding, apart from being used by Bajcsy (1988). For example, it is written in the introduction of the book *Active Vision*, edited by Blake and Yuille (1992), that active vision 'refers ... to *strategies* for observation', and that 'visual sensory data is analysed *purposefully, in order to* answer specific *queries* posed by the observer' (italics being added).

detailed epistemological discussions in part III (chapters five to seven).

Those epistemological discussions about the concept of goal can be briefly introduced as follows. When the organisms of a certain species encounter certain environmental challenges with certain inherently compelling tasks to accomplish (e.g. detecting certain predator cues), they gradually derive (through self-organisation or natural selection) certain relevant goals, their supporting (specialist) mechanisms, and the between-mechanism connections. As a consequence, those organisms become gradually more competent to accomplish those tasks. This is a process of *competence generation*, in which characteristics of the ecological niche of that species are gradually 'reflected' in capacities of organisms. This point will be discussed in chapters six with the notion of *inverse ecological niche* (see Section 6.5.1, page 255).

Similar to the concept of goal, the explanatory, probing, and searching activities of sensory organs are not based on the prudence of a homunculus *who* resides internally in the organism, but instead on the *facilities* which support the *effectiveness* or *efficiency* of computation. The term 'effectiveness' is generally interchangeable with another term – 'reliability', which is less often used in the context of mobile robotics. Both terms (effectiveness or reliability), group together two different references – the applicability (including accuracy) and non-fragility of mechanisms. By contrast, the term 'efficiency' means primarily the economy of computational resources, such as time, space (memory), and attention.

In our detailed discussions of the active perception researches, we will see the effectiveness and efficiency of computation supported by various types of processes, such as (1) the *a priori* knowledge adopted in the form of the Lagrangian template in support of a dynamical Kalman filter (which subserves dynamic contour tracking (see Section 4.1.3 of the present thesis, beginning at page 123)), (2) comparison of contours (e.g. the sideness of a contour and the free-space between would-be rigid objects) from various viewpoints (e.g. Adept, see Section 4.2.1, beginning at page 126), and (3) navigation (Dickmanns' car, see Section

4.2.2, page 132)), and the reinforcement-learning algorithm adopted to facilitate the learning of navigation via situated activities (e.g. Sprite, see Section C, page 361; e.g. the capability of categorisation implemented in the mobile robot by Scheier and Lambrinos (1996), see Section D.3, page 379). The above processes are parts of autonomous systems, where no intentions or homuncular prudence are presumed. Thus, the key notions adopted by Bajcsy (1988) to specify her active perception perspective, which she claims as a scientific paradigm, receive epistemological grounds.

What Makes Active Perception be Active – Process or Product? In the beginning of this chapter, we raised the issue that perception could not be highly adaptive without small-scale sub-systems. Because their role in perceptual performance is to make perception be active, we must clarify the notion of activeness before we set off to see its detailed mechanisms. To put it in another way, the question is *what makes perception be active*, given that the autonomous small-scaled sub-systems work under real-time constraints in the real environment[15].

Real-time performance may be taken as a criterion of being active, as is suggested by intuition. However, this is inadequate, because such a criterion is but a *result* of the autonomous systems with certain *arrangements*. It is, indeed, the way of arrangements that makes autonomous systems be active, but the performance under real-time constraints is the result, not the criterion.

Although the performance in the real environment is a goal of the active perception perspective, setting a goal like that is not the same as identifying the essential processes which underpin active perception. The process, rather than the performance, is still what is most important in the scientific *explanation* of active perception, because considerations of it engage with the understanding of active perception in all the relevant organismic constraints in the real environ-

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[15] Please compare a similar but different question which we raised in the previous section: what makes active perception *work*, given that it is implemented in *autonomous* systems which work under *real-time* constraint in the *real environment*? Note that the activeness of perception presume the well working of its sub-systems at the three scales. Hence the present question (i.e. activeness) is a sub-question of the previously raised question (i.e. working).

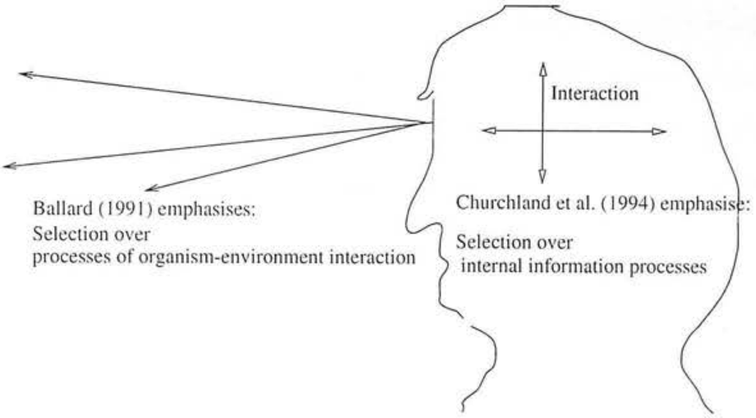

Figure 3.1: **The AB and BC Perspectives of Active Perception.** Both Ballard (1991) and Churchland *et al.* (1994) have a common concern which indicates the activeness of active perception: the stepwise selection of *information* which leads to the accomplishment of required tasks. Those two approaches only differ in their respective means of information selection, namely, one (in Ballard (1991)) being the data collection between an organism and the environment, while the other (in Churchland *et al.* (1994)) being data interpretation within the brain.

ment. As a consequence, it is process, rather than performance, that identifies the activeness of active perception.

3.3 Comparison and Integration of Two Approaches

Ballard (1991) and Churchland *et al.* (1994), in their respective approaches to active perception, identify the selection over useful information as being *essential* to activeness. For the effective performance in the real environment, there *must* be selection over useful information, although the selection may be carried out in different ways.

Comparison. Ballard (1991) and Churchland *et al.* (1994) hold different views regarding the criteria for active perception. Ballard (1991), together with most authors in Blake *et al.* (1992), emphases the adoption of economical processes which *make available* the information needed for accomplishing the required tasks. Such processes are typically seen in an early visual stage. They subserve data *collection*. By contrast, Churchland *et al.* (1994) focus on the information provided by the *interaction* of brain modules, which typically happens in a late visual stage. Such processes relate to *interpretation* of the information provided in the retinotopic maps. Thus, the distinction between these two approaches is clear: one emphasises data collection, while the other focuses on data interpretation.

Integration. These two perspectives are not trivially related to visual stages, or to the positions *across or beyond* the skin (specifically, between an organism and the environment) or *within* the brain. They have a common concern which indicates the activeness of active perception: the autonomous stepwise (thus gradual) selection of *information*, such that what a later process is to carry out depends on what information has been gained and what is still needed for the eventual accomplishment of the required task (figure 3.1).

What distinguishes the two perspectives is their respective emphases on the perceptual activities, one emphasising on the collection of useful data, the other on the data interpretation and interconnection within the brain. However, both means of information selection make perceptual processing easier, and consequently facilitate active perception with regard to its real-time performance. In addition, both emphases presume sensory-motor activities. The processes emphasised in both perspectives are not simply processes at different computational stages, because they both need their respective sensory-motor activities.

Summary Active perception research considers perception to be active, as opposed to the full reconstruction of a 3-D visual scene from (2-D) retinotopic maps via bottom-up and hierarchical processes. Two main lines of argument support this view – AB and BC perspectives of active perception.

These two perspectives have certain commonalities, namely an understanding of the importance of task-specific facilities and observers' movements for perceptual computation, in order to gain access to more relevant perceptual features.

Despite their commonalities, those two perspectives contain significant differences in emphasis. According to the AB perspective, iterative perceptual processes seemingly 'strive' to *make available* the visual information *needed* for the required visual tasks with the support of sensory-motor and bodily actions. By contrast, according to the BC perspective, perceptual processes constantly build the mutual coherency of perceptual properties, within and across modalities.

3.4 Gaze Control

Among the various phenomena of active perception, gaze control is an archetype. The performance of gaze control, as Ballard (1991) states, is vitally important in the paradigm of *active* vision, because it serves to maintain the exocentric coordinate frames and other required visual information. The capacity of gaze control in the mammal consists of a variety of autonomous visual sub-systems, including accommodation, aperture, binocular vergence, saccades and foveation, pursuit (e.g. Collewijn and Tamminga 1984; Robinson 1968, 1987; to mention only a few), and the *cooperation* between them. Similarly, artificial autonomous systems of vision can perform the skills of gaze control in many respects, as we will see briefly in this subsection.

First, certain artificial autonomous systems, based on a variety of designs in (real[16]) mobile robotics, have demonstrated capabilities of cooperative accommodation[17] (focusing), binocular vergence, and stereopsis for surface reconstruction (Abbott and Ahuja 1988). Second, certain other autonomous systems demonstrate binocular vergence, smooth pursuit, and the cooperation between them (Coombs 1991). Third, still other artificial autonomous systems demonstrate the cooperation of accommodation, vergence, stereopsis, and foveation (Brown *et al.* 1992, see our discussion below). Last, but not of least importance, an implemen-

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[16] That is, it is not simply simulation, although real mobile robots may use computer simulation to test the design before the design is implemented in real robots.

[17] Accommodation in the vertebrate eye is the autonomous process of changing the curvature of lens. By fine-tuning and focusing the lens, the process fine-tunes and focuses the lens, which controls both the amount of light rays issued from a distant target and the degree of light refraction in the eyeball, with the effect of convexing a refracted light ray to a particular point on the retina. The degree of changing the curvature depends on the distance of the target object (Schiffman 1996, pp. 61-63).

tation of attentive control, based on the human oculomotor control described by Robinson (1968, 1987), directs camera saccades and foveation to perform seemingly explanatory-predictive behaviour (Clark and Ferrier 1992), an endeavour that we described in the previous section.

In the following discussions we need to extract the strategies of robotic design and thereby construct epistemological explanations, to see why the capabilities of gaze control can be accomplished by the artificial *autonomous* visual sub-systems without recourse to a sort of 'motionless mover' – intentional prudence. Those artificial autonomous sub-systems, notwithstanding, appear to be capable of performing certain activities similarly (but not actually) to intentional prudence, especially the *seemingly* explanatory-predictive endeavour which guides various aspects (vergence, pursuit, saccades, etc.) of the gaze.

Due to the limitations of space, we cannot discuss the cooperation between *all* the visual sub-systems, and hence will limit the number of focuses, by disregarding aperture and accommodation. Thus, we will discuss vergence and pursuit, on the one hand, and the attentive control of saccades, on the other. These two visual sub-systems can be found respectively in the third and last robot autonomous systems mentioned above. The former (the third system) can be seen as a precondition of the latter (the last system). For the whole system of gaze control, vergence and pursuit can be regarded as a large-scale visual sub-system arranging the movements of the two cameras ('eyes'); by contrast, the sub-system of the attentive control stands alone in dealing with subtle computation over the attended information, with the result of providing sufficient information for arranging the continual saccadic movements, that is, the path of emphasised foveating visits and re-visits. These cooperate completely autonomously, without sacrificing the adaptability required in the unpredictable environment, as we will see from their robotic design and implementations.

In the early stages, the human visual system must *adjust* its direction and position in order to collect *stable and relevant* visual information (in relation to certain required tasks) for the analysis carried out at later stages. The adjustment for the collection of such visual information, in general, consists of six stages. Two of them, to wit focus and appropriate aperture, subserve the adjustment of internal eye (camera[18]) state. Three others, namely saccades, vergence and pursuit, serve to adjust the interrelations between the two eyes, body (specifically – head, shoulders, and body gestures), and the gaze target (i.e. the target object). The remaining stage, i.e. tracking, is to adjust the visual system in the brain, by adopting suitable processes for identifying the shape of the target object and predicting the object's trajectory, for example, in the vision of a stationary mosquito, a running tiger, a moving missile, an approaching shark, or (via a microscope) a deformable cell.

3.4.1 Focus

The term *focus* (accumulation) is a category for a single eye. With a certain curvature of the lens, the eye brings the optical flow, through the eyeball, precisely to the retina cup. A focus is consequently obtained. The same point of the target object is reflected on a single point on the retina, neither to a point in front of the retina nor to a geometric point behind it.

This function (focus) is a common feature of cameras, relating to the distance of the target object. A target object can be focused on, i.e. brought to the retina properly, if it is a certain distance away from the camera, from as little as about 24 cm (depending on the type of lens) to infinity. While focus can be hand-crafted in a camera, the lens of the human eye is autonomously controlled. The process of focusing or defocusing consequently gives rise to depth information (i.e. distance of the target object) monocularly (Hwang *et al.* 1989; Pentland 1987), just as we can measure distance from a camera with hand-crafted focus function.

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[18] In this chapter, we use 'eye' and 'camera' interchangeably. The one can be viewed as a metaphor for the other. The context will show which is strictly talked about.

3.4.2 Appropriate Aperture

By contrast to controlling focus by its curvature, a lens controls the amount of light by its aperture. In addition, the size of the aperture controls the 'depth of focus', i.e. the area in the visual field around the focused target where the sensitivity of depth is critical. In photography, a larger aperture makes the depth of focus smaller, and vice versa. As with focus, aperture is usually controlled in a camera by hand (i.e. externally), while in a system of active vision it is controlled autonomously. For an artificial visual system, it is important to maintain sufficient light levels for the image sensor (Clark and Ferrier 1992).

3.4.3 Saccades

Visual saccades consist of a continual sequence of single saccades, each of which takes a period of about 200 milliseconds, which is much longer than the duration of vergence and pursuit movements. The visual saccadic system consists in the control of two sub-systems: attentive control, which determines the next position to foveat by a saccade movement; and oculomotor control, which converts the information about that next position into corresponding motor actions and accordingly 'drives' the eyes to foveat that position. Above, we have briefly described the attentive control sub-system. The oculomotor control sub-system for saccades, in its real-time action, is closely related to the pursuit systems (Robinson 1968; Brown *et al.* 1992; Clark and Ferrier 1992), as we will see. Both saccadic movement and gaze pursuit, as we will see, presume the availability of vergence. For this, we must provisionally set aside the interrelation between saccade and pursuit, and understand vergence beforehand.

The mechanisms of saccadic movements are described as follows. The adjustment of gaze is required for both moving and *stationary* observers and objects, because the eyes need to keep on moving continually, from one location to another, in order to let each *fovea* (a tiny area on the retina cup which provides the best resolution of visual features) encounter lots of relevant target positions for the required task, as is evident in the *saccades* of eyeballs. This means that a visual system cannot be completely stationary.

Saccades consist of a continual sequence of eye movements, each of which is a pre-attentive stage wherein certain visual primitives (such as colour, line ends, spatial frequency, motion, line orientation, binocular disparity, and texture (Clark and Ferrier 1992)) are sampled in parallel across the visual field (Treisman and Gelade 1980). As is indicated by Robinson (1968) and modelled by Clark and Ferrier (1992), a system of *attention control* serves to measure such samples, depending on differently required tasks, by assigning those primitives different weights (called different 'saliency'). For each assignment of weights, the system computes the combined weights of the sampled points, with the result being a 'saliency map'. As a consequence, a point of maximum saliency is determined, which is regarded as a *focus of attention* – the point for the *destination* of the next saccade. With such a method of computation, changing the assignments of weights results in different saliency maps, and in turn different maximum points are determined as the subsequent destinations of the continual saccadic movements.

For humans, the duration of determining each saccadic destination, i.e. the time interval between two saccades (which is called the *latency* of the human saccadic system), is measured to be about 200 milliseconds, so there are four to five saccades per second. This is less frequent than vergence or pursuit movements (Robinson 1968).

As described above, the saccadic movements can foveat and re-foveat the most salient points in the visual field. This makes the saccade system appear to be *clever*, in support of the required visual tasks. The attention control sub-system seems to be capable of deliberating about the important features for a certain required task. However, this is not really mysterious, but is accomplished by computing the combined weights of the sampled visual primitives and re-computing them with the continual changes in the assignment of weights. Everything is determined autonomously, but the adaptability of the saccadic movement remains impressive, nonetheless. The saccadic movement, specifically, adapts to the important features of the required tasks, with the frequency of about 5 saccades per second. Intuitively, the saccadic movement appears to *explore* important features in the visual field in support of the required tasks. What is interesting is that the saccade system not only is autonomous, with a high degree of modularity, but also retains high adaptability. In this regard, the emergence of the saccade system is really in need of explanation, for modularity and adaptability usually conflict in both creatures and designed devices. This is the topic for part III (chapters five to seven). In fact, this is the main theme of the present thesis.

3.4.4 Vergence

Unlike the term focus, the term *vergence* is a *binocular* category, which denotes the process of fixating both eyes in opposite directions with the result of intersecting the optical axes of the two eyes on the target object (Figure 3.2). The intersection of the two optical axes is called the *gaze target* (Brown *et al.* 1992).

A pair of binocular eyes (or cameras) of a binocular visual system has several degrees of freedom. First of all, a single eye presents two degrees of freedom, namely vertical rotation (by changing the degree of tilt) and horizontal rotation (by surveying along with the pan on which the eye fixes) (Figure 3.2). If both eye are fixed on the same pan (consequently with the same degree of tilt) and maintain horizontal rotation simultaneously, three further degrees of freedom remain. Two of them function similarly to the vertical and horizontal rotations, but are subject to the movement of the head, instead of the eyes. The remaining degree of freedom for the two eyes is the *distance* of their fixation point (where the optic axes of the two eyes intersect) from the middle point of the two eyes. The functionality of the vergence system is to control the respective optic axes to fixate at a point with the right distance – namely, the distance of the target object (figure 3.2). When fixation at the target object is achieved, the object is pictured (along with the optic axes) at the foveae of the cameras, where the highest degree of visual resolution can facilitate the analysis of visual information at the maximum rate.

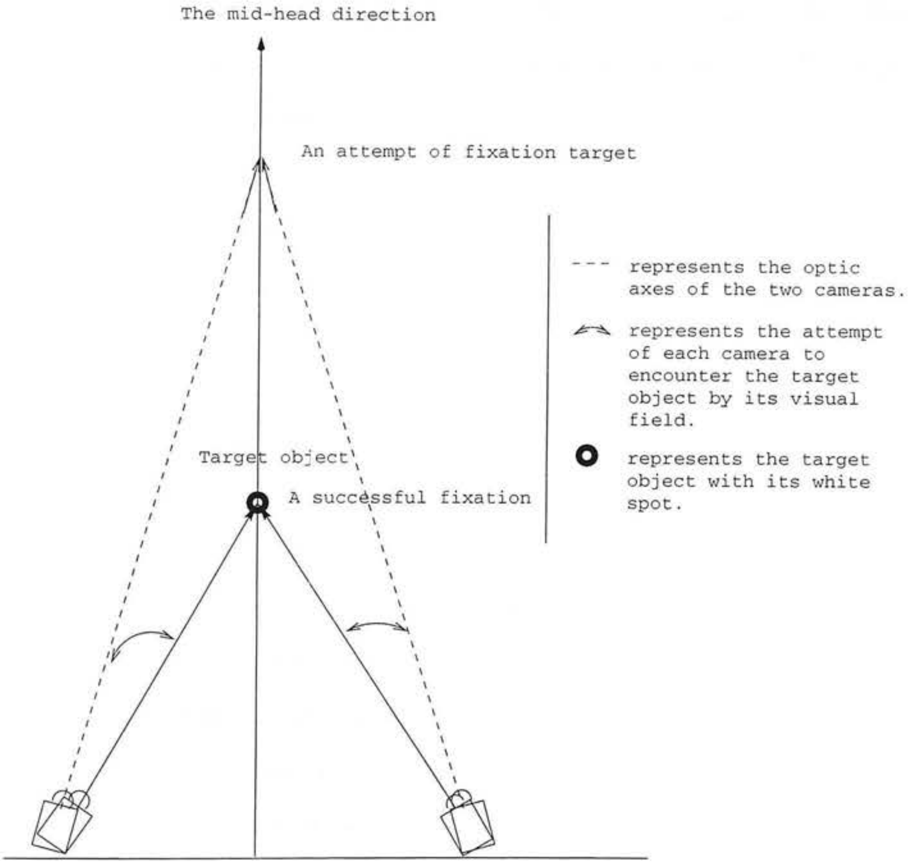

Figure 3.2: **Vergence.** The attempt of vergence remains unsuccessful until the computation of the pictured object on both cameras manifests zero-disparity. When the condition of zero-disparity is achieved, the two cameras coincide at a fixation point. Note that the vergence control system of Brown *et al.* (1992) presumes the symmetric movement of the two cameras, which simplifies the task of vergence.

Note that the target distance is exactly the *depth* determined by the low-level function of the binocular visual system. Such an identification qualifies the vergence system, in its judgement of fixation distance, to take advantage of various depth cues. The most direct one is binocular disparity. Other cues are motion, texture, shading, and anything that signals the change of the target depth, such as the measurement or prediction of self-motion (Brown *et al.* 1992). We first discuss the achievement of vergence by means of computing zero-disparity, and leave those other cues to later.

Determining Vergence by Computing Zero-disparity. Before vergence is successfully achieved, the visual system is incapable of computing the distance of the target object. The distance is, thus, not already available. The computation with recourse to 'where' would consequently be difficult. The achievement of vergence cannot begin with the *geometrical* information of the target object. Instead, undertaking a 'what' strategy to achieve vergence would be more feasible, in the sense that vergence is seen to be a consequence of analysing the *morphologies* of the target object on the 'retinae' of the respective cameras. This is seen in Brown *et al.* (1992). In their design[19], both cameras are directed by a feedback control system based on zero-disparity computation, by comparing the same visual features gathered from two angles which naturally manifest various degrees of disparity. The result of zero-disparity computation is that a point with zero degree of disparity is singled out for positioning the would-be fixation point.[20]

The zero-disparity computation is grounded on an assumption: the fixation point necessarily has a stereoscopic disparity of zero, with the points nearer to it tending to have smaller disparities. This assumption is confirmed in the neurophysiological understanding of mammalian binocular eyes (Churchland 1995).

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[19] Brown *et al.* (1992) simplify the vergence control system by assuming *symmetric* vergence control. They acknowledge that this is not necessarily the case for vergence control. Their modelling of robotic vision is thus a simplification. As a consequence, their vergence control system cannot fixate anywhere other than those points on the line of the mid-eyes direction. To fixate elsewhere, the visual system must move (by translation or rotation) its head, on which the two cameras are fixed.

[20] A good illustration of zero-disparity computation can be found in Paul Churchland (1995).

Thus, the aim of vergence is to identify the fixation point via the identification of the point of zero-disparity.

Notice that the achievement of vergence in Brown *et al.* (1992) is typical of a behaviour-based approach, where vergence is seen the required behaviour. The information needed to achieve the required task is provided by a system of *feedback control* which filters out visual information *iteratively*, by comparing the disparities of the target object pictured on both cameras and then feeding back the provisional result of comparing an area with a *smaller* stereoscopic disparity. With the feedback processes running iteratively, the feedback control system ends up with a point of zero-disparity, which is the correct position for vergence fixation.

Significantly, this feedback control system achieves the required vergence in real-time, specifically in-between one or two frame times.[21] A frame time is 33 milliseconds, and the computation of the zero-disparity point for positioning the vergence fixation in the visual windows of 32-32 pixels takes 51 milliseconds!

A side-effect of fixation, in the imaging work of Brown *et al.* (1992), is the generation of a rough contour of the target object, specifically a stereoscopic outline image of the limited area near to the zero-disparity point. This can be seen as a basis for further achieving a stereoscopic image with various degrees of depth (see P. M. Churchland (1995), for the computation of three degrees of depth).

With this computation, the point of zero-disparity is singled out for positioning the would-be fixation point. This result is passed over to the host computer for the motor control of changing camera directions. The host computer converts the pixel disparity to angular coordinates, and then issues identical and opposite vergence velocity commands[22] to the camera motors.

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[21] A frame time is the duration between two picture-taking activities with a camera. Intuitively, a 'frame' means an instance of picture-taking.

[22] Note again that Brown *et al.* (1992) simplify the vergence control system by assuming symmetric vergence control. Thus, the vergence velocities of the two cameras are symmetric in opposite directions. Also note that this is not necessarily the case for vergence control, as their modelling of robotic vision is obviously a simplification.

The human vergence system, of course, does not presume symmetric movements of both eyes, and hence is capable of detecting objects aside from the mid-head axis. The asymmetric binocular movements have more degrees of freedom. In the present thesis, due to the limitation of space, we do not intend to discuss how this is done.

The vergence control system implemented in Brown *et al.* (1992) presents a counter-example to the passive perspective of vision, mainly for two reasons. First, visual processing does not commence at the 2-D retinotopic maps. The visual system needs to take actions to make available relevant retinotopic information by vergence control. This is done *before* sufficient information is already available there. Second, the visual processing of vergence does not serve to reconstruct the retinotopic maps, but aims to *fixate* the two optic axes by taking advantage of the binocular stereoscopic disparities. At this very early stage of visual processing, this information is not used for the reconstruction of depth but for the accomplishment of vergence, as we have seen. In contrast, the effect of vergence can be seen as a facility for maintaining the exocentric coordinate frames which are a characteristic of active vision.

In our discussion so far, we have seen how the vergence system achieves a single instance of vergence. Now, we need to move on to discuss gaze pursuit, in order to see how the visual system *maintains* vergence in moving conditions, i.e. when objects and/or observers themselves move.

3.4.5 Pursuit

The movements of organisms, visual organs and the objects in the environment, lead to the target moving *out* of the fixation point, for reasons described below. During the 200ms *latency* of a saccade movement, a position as the destination of the subsequent saccade is derived by the saccade system, but the target object would not have been keeping stationary at that position. Instead, it moves elsewhere, and hence a position error occurs for saccadic movement. Such an error must be compensated for in order that gaze (focus and vergence) can truly keep up with what is suggested by the system of attentive control. The actuator of the oculomotor system must not drive the saccade to the initially computed destination without taking account of a required compensation.

The question is how the pursuit system does this effectively. How does the pursuit system 'know' *where* the attended position has actually moved to? Granted that it knows, a further question arises. During its drive there in a certain period of time, might not the desired attended point move away again? Thus, the chase of an attended position would be constantly lagging behind, if the pursuit system (like the saccade system) works on the basis of absolute position.

The human visual system does not try to compensate the position error (i.e. to re-fixate the target) from scratch. That is, it does not maintain it via the vergence system again, but by another system – the pursuit system, which serves to maintain the tracking (with respect to gaze movement) of the moving target, within a duration shorter than the saccadic latency. This is confirmed by Robinson (1965), who shows that the pursuit system is a sampling system, like the saccade system, but with a sampling rate much higher than that of the saccadic movement, i.e. with a sampling duration much shorter than the 200 ms saccadic latency. It is reported that the *cumulative* position error may turn out to be compensated for by a single saccade, hence pursuit movements are not always smooth (Collewijn and Tamminga 1984).

The pursuit mechanism is described in detail as follows. As we mentioned previously, during the latency of a saccade the moving target causes a position error for both focus and vergence, and this must be compensated by the pursuit system. Thus, a pursuit system must minimise two measures of error – (target) position error and (retina) velocity error (Brown *et al.* 1992).

As positional error accumulates for many reasons (e.g. 'delay in the system, noise in the position readings, problems of robot head velocity computation') (ibid. p. 134), the extent of target slip increases, and the fixation location gradually departs from the target object. Furthermore, an erroneous velocity, i.e. a velocity of the oculomotor actuator which does not cope with the velocity of the moving object, would also divert the gaze from the target. To keep up with the moving target object, then, the oculomotor actuator must take account of the position error and velocity error to manage compensation for the correct destination.

A key notion of pursuit movement is that the visual system is not entirely insulated from the moving target during the saccade latency. Certain visual capabilities remain functioning, including measurements of the moving target and the internal predictions of its trajectory.

Computation of Compensation *after* the Saccade Latency. This is relatively simple. If the visual system were entirely insulated from the moving target, then it would be impossible for it to compensate for the two kinds of errors, because the saccade system would have no information about the (position and velocity) errors.

Slightly relaxed, even a vergence system with its computational duration *interpolated between* saccade latency, as opposed to the incorporation into them, does not help much, either. To re-fixate a target object is surely not impossible for a vergence system, but the gaze might accordingly be lagging behind permanently. In such a circumstance, the vergence (i.e. re-fixation of both eyes) functions *after* the target object has moved away at the end of the latency period in question. Since vergence starts later, the vergence process takes a certain period of time *in addition to* the time of the saccade latency, despite this being a period of time much shorter than the 200-milliseconds of the saccade latency. Meanwhile, the desired saccade destination of the moving target would have moved away from where it was previously determined by the attention control system. This, in itself, leads to both a position error and a velocity error. The difficulty remains.

In the analysis of the question of pursuit, the two most serious problems are: that *both* the previous vergence point and the saccade destination move during any period of time; and that any computational process takes time (including saccade latency or the duration of a vergence process), however short it can be. Computation of vergence after the completion of a single saccade would leave the pursuit movement permanently lagging behind.

This problem arises when the vergence system computes a vergence movement after the saccade latency. A straightforward resolution of this problem is to compute a vergence movement *during* the saccade latency. This is possible since the vergence system and the saccade system are treated as mutually independent. In this case, vergence still interpolates saccades if the vergence movements are *separate* from the saccades. Alternatively, the computational result for the vergence movement could be *incorporated* into the next saccade as a modificatory amount, and the oculomotor activities would be consequently less laborious. From an economic point of view, this is a better resolution.

However, the pursuit movements based on vergence control would remain awkward because it leaves out a variety of useful information without taking advantage of it, as we will see shortly. This is a fundamental difference between vergence control and pursuit.

Overshoot. An alternative way of compensating for the position and velocity error is to provide an *overshoot* in the response step, as suggested in Brown *et al.* (1992). Specifically, *during* the saccade latency the pursuit system combines measurements of the target and predictions over possible states of the target in '*fixed proportions*', under certain correct *assumptions* about noise or the target state, to produce an optimal *estimate* of the target state (Brown *et al.* 1992, p. 128; italics added). There is no need, then, to compute, with an extra period of time other than the saccade latency. Nor is there a need to sort out the *absolute* position or velocity errors. Provided that the assumptions are near to the actual target movement and that the fixed proportions have not been estimated, the predicted overshoot will compensate the errors to a significant extent.

A useful assumption about a moving target is *path coherence* (Jain *et al.*

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A useful assumption about a moving target is *path coherence* (Jain *et al.*

1995), which is also adopted in traditional computational vision in its reconstruction of object trajectory. That assumption can apply to active vision in gaze control, and specifically to pursuit movement. It states that the location of a given point, its scalar velocity, and the direction of motion would be mostly unchanged from one to the next frame time, i.e. not changing instantaneously. In brief, movement of a physical object has 'inertia' (ibid., p. 443).

A similar assumption is the *internal constancy* of a target object, and this is widely adopted in tracking (e.g. Harris 1992; Terzopoulos and Szeliski 1992). Here, it is assumed that the physical principles of the target object remain the same. For a rigid object, it is straightforward. For deformable objects, such as fingers, the internal constraints of fingers and hand remain useful for the prediction of spatial properties, such as shape, location and velocity (Terzopoulos 1987).

With either of these two assumptions, a later movement (which leads to the position and velocity errors) can be predicted from its previous trajectory in a duration as short as a single frame time (33 milliseconds, for the vergence system we previously discussed). If it is along this line of reasoning, it is straightforward to derive that the amount of *an* overshoot for *computer* vision needs the accumulation of position and velocity errors for 6 to 7 (i.e. 200/33) frame times. By contrast, it is reported that the human pursuit system is a *continual* sampling system, or at least a system with a sampling rate much higher then the saccadic system (Robinson 1965). During the saccade latency, there would be sufficient times of sampling for the pursuit system to accumulate position and velocity errors, in exchange for an *over*shoot.

Compensation on the Basis of Stereoscopic Disparity. An alternative to compensation on the basis of overshoot is the compensation of errors on the basis of zero-disparity. Certain methods of the pursuit control can be built on the basis of the cumulative stereoscopic disparities of the target in the retina, to estimate the position and velocity errors (Clark and Ferrier 1992). In a sampling period, the binocular disparity of the target[23] can be computed; for more sampling times, such disparities can be accumulated to trace the position error. In addition, the change of those disparities can be computed to signal the magnitude of the velocity error. The high rate sampling of the pursuit system can compute by comparing the gradually sampled data, the cumulative disparities and the trajectory of their change, with regard to the positional change, and the change in scale velocity and directions. Thus, the cumulative position error and velocity error can be transformed into oculomotor activities, and added to the oculomotor movement of a saccade, to compensate for the position and velocity errors during the saccade latency.

3.4.6 Tracking

Pursuing an object can also be termed the 'tracking' of that object. This term 'tracking' is somewhat ambiguous, however. It can be understood in a broad and in a narrow sense. According to the broad sense, tracking means the maintenance of gaze on the moving target. In this sense it is similar to pursuit movements. According to the narrow sense, tracking an object additionally requires the identification of its shapes. In the context of active perception research the term 'tracking systems' is understood in the narrow sense. This sense of tracking is the subject of the next chapter.

3.4.7 Summary

The control of gaze is a combinational outcome of six movements – focus, appropriate aperture, saccades, vergence, pursuit, and tracking (in the broad sense) – each of which is implemented by a sub-system of gaze control. Among those six sub-systems, two are repeatedly referred to in the building of the conceptual foundations of task-level emergence – attentive control of saccades and the control of pursuit movements. Discussion has shown that they are active systems, in

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[23] The target can be detected across the different sampling times, because the main features of the target object remain constant during the saccade latency.

that the sensory organs move in order to gather information step by step for the required tasks. In addition, both of them take advantage of pre-fixed exploitative heuristics of visual features and motions. However, the course of computation is shown to be incrementally affected by previous judgements which are affected by unpredictable environmental factors.

The computation at issue is largely contingent, for the following three reasons. First, the determination of a next process depends on the previously gathered information in comparison with the information still needed for the required tasks. Second, both the *weights* of visual features and the measured position and velocity *errors* of motion trajectories are not pre-categorised values. Third, such weights and errors are affected by various environmental and within-system factors which both *arise* contingently.

3.5 An Epistemological Framework for Active Perception.

The active perception systems studied in these two chapters (three and four) can be largely understood on the basis of a general epistemological framework, as sketched below.

A capability to be implemented in support of a required task must[24] *settle* two extremes of an emergent trait – adaptability and modularity (which makes possible the autonomy in active perception systems). The contrast between modularity and adaptability may take various forms, e.g. between stiffness and flexibility, between template and uncertainly, between prior knowledge and modification, between continuity and local conditions, between model-based and stochastic approaches. Because the implementation of a *capacity* may be subject to those different forms of settlement, a particular *mechanism* of implementa-

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[24] Notice the *prescriptive* nature of epistemology in this statement. It *explains why* a robotic implementation can be endowed with a capability on the basis of autonomous systems. Our envisaged epistemological framework will not serve to *describe* the state of art of the present robotic implementations of active perception.

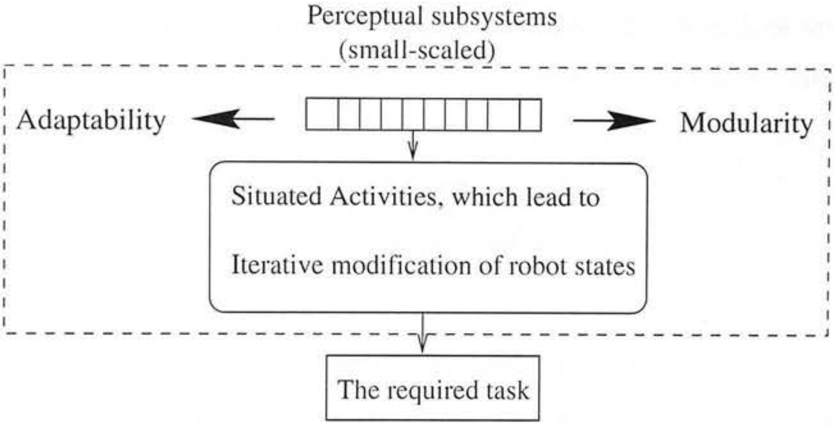

Figure 3.3: **The Epistemological Framework of Gaze Control.** The sub-systems of active perception settle adaptation and modularity by *situated activities* which *modify iteratively* the robot states, with the effect of carrying out the required tasks. Note that certain sub-systems serve to capture pre-formed knowledge, while certain others serve to respond to random factors. The dot box indicates that gaze control is grounded on the interactions of various sub-systems.

tion must reflect the settlement of contrasts with a particular form shown above (Figure 3.3).

The sub-systems of active perception accomplish this by *situated activities* which *modify iteratively* the robot's states, with regard to their architectures and weight of valued information parameters, with the effect of carrying out the required tasks (as shown in Figure 3.3).

To put it in another way, the iterative modification can be analysed from the point of view of various processes on three scales. At the smallest scale, single sub-systems of active perception – e.g. the attentive control of saccades – select information stepwise on the grounds of what has been done and what remains to be done in order to carry out a requisite stage of the required task.[25] At the intermediate scale, the iterative activities of those sub-systems will support a capability/capacity, e.g. gaze control. At the largest scale, the cooperation of a variety of systems, such as gaze control, tracking, and the planning of focus attention, leads to the performance of required tasks, such as navigation.

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[25] It can be said that the selection is grounded on the *history* of the agent's previous situated activities.

The difference in scope between these three scales is not trivial, as we will see in the following two chapters. It reflects the sophistication of nature with regard to the emergence of perceptual capacities: the two extremes of an emergent trait (i.e. modularity and adaptability) are accomplished simultaneously by *linking a variety of small-scaled sub-systems.* This sophistication can be seen in two subtle arrangements of emergence.

The first of these is that small-scale sub-systems are themselves both modular and adaptive to certain specific aspects of the real environment. Each sub-system seems to have its specific purpose, for it facilitates perception by capturing certain aspects of the perceptual target in the real environment. Certain sub-systems serve to capture pre-formed knowledge, while others serve to respond to random factors. It is a small autonomous system (a module), and is small in the sense that it carries out *effectively* a very specific aspect of perceptual performance in the real environment.

For small systems, in contrast to large ones, it is comparatively easy to be autonomous and adaptive simultaneously. Of course, the overall performance arising out of these small-scale sub-systems is dependent on the challenge of mutual coherence between those sub-systems. This (mutual coherence) is the second subtle arrangement of emergence, which is accomplished with recourse to a series of adaptational processes – the gradual adaptation from simple to complicated organisations through both internal dynamics and the situated activities in specific ecological niche. The process of gradual adaptation is of vital importance in explaining the emergence of active perception, as we will argue, largely because it sheds light on the *linking problem* of those highly differentiated sub-systems, by explaining the interconnections between those sub-systems in terms of *gradual* differentiation, where the differentiated sub-systems can be consequently seen as being inherently well-aligned in the process of differentiating each single sub-system. This topic will be fully discussed in chapter five.

3.6 Summary

This chapter provides an overview of active perception, comprising its main theoretical perspectives, an archetype (gaze control), and an epistemological framework for explaining how various modules cooperate for accomplishing the required tasks.

Chapter 4

Implementation of Tracking and Visual Planning

4.1 Tracking

Tracking of a target object has two main goals, namely holding gaze on it and identifying its contour. The former goal is a matter of gaze control, which we have discussed in full previously. For the latter goal the task of tracking may take various forms, including: tracking an object with a rigid shape; tracking a moving target; and tracking a target with elastic shapes, such as fingers, lips, and amoebae (note their changing shapes). As we will see, a variety of mechanisms are needed but commonly have the requirement of compromise between modularity and adaptability, regardless of how the compromise is reached. However, the compromise may take various forms, as we mentioned previously (see Section 3.5, page 110) – namely, balancing stiffness and flexibility, template and uncertainty, prior knowledge and modification, continuity and local conditions, or alternatively model-based and stochastic approaches.

4.1.1 Snake

Snake is introduced by Kass *et al.* (1988) and Terzopoulos (1987) (see Terzopoulos and Szeliski (1992), p.4), an algorithm for tracking contours, on the basis of splines which may be rigid or elastic, stationary or moving.

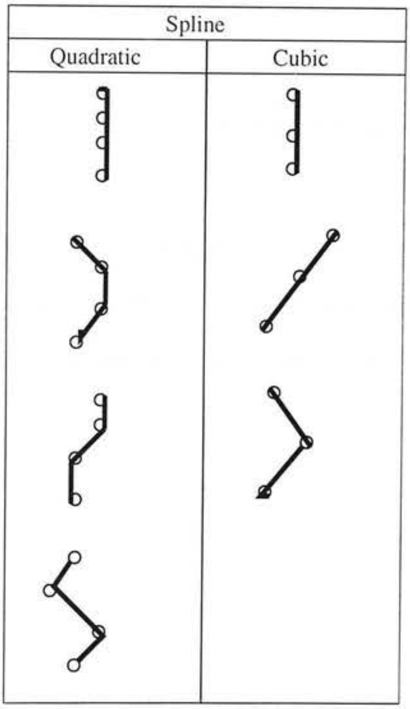

Figure 4.1: **Some Basic Forms of Spline – Quadratic and Cubic Splines.** It is re-drawn with configuration from Curwen and Blake (1992) table 3.1, p. 49.

Splines (figure 4.1) in the snake algorithm (Snake, henceforth) are controlled by an energy-minimising function which responds to three sources of forces – internal, image, and external forces. Each source of forces has its particular role in determining the settling shape of the snake, and the forces of different sources are complementary in the process of the determination. The internal forces of the spline impose piecemeal smoothness constraints to maintain local continuity of the spline; the image forces drag the spline to settle locally in the forms of certain salient image features such as edge, line, termination point, and even subjective contours. By contrast, external constraint forces (such as a pulling force manipulated by a user, by an attention mechanism, or by a high-level interpretation) do not serve to determine the shape of the spline but instead push the not yet formed splines near to a local minimum (Kass *et al.* 1988).

Forces of different sources are aligned in the determination of a single spline by simple addition:

$$E^*_{snake} = \int_0^1 E_{snake}(v(s))\,dx = \int_0^1 E_{int}(v(s))\,dx + \int_0^1 E_{image}(v(s))\,dx + \int_0^1 E_{con}(v(s))\,dx \tag{4.1}$$

where E_{int} represents the internal energy of the spline, E_{image} gives rise to the image forces, and E_{con} influences the external constraint forces (Kass *et al.* 1988, p. 323). These three forces interact and thereby determine the eventual shape combined by splines.

Single sources of forces can be decomposed in a similar way. For example the energy function of image forces is determined by the energy of line, edge and terminal, which are combined by addition:

$$E_{image} = w_{line}E_{line} + w_{edge}E_{edge} + w_{term}E_{term} \tag{4.2}$$

where E_{line} is the energy function determining lines, and w_{line} is the weight assigned to the energy in the distinction between light or dark lines, while w_{edge}, E_{edge}, w_{term} and E_{term} can be understood in a similar way. Note the interconnection between weight and energy by multiplication and the further interconnection by addition, which determines the interactions between those components. The interactions with various component forces lead to *slithering* movements of the snake contour while the energy functions are minimising their energy, which is why the envisaged algorithm is termed 'Snake'. An interaction of image and external forces is illustrated in figure 4.2.

The Snake can be applied to tracking subjective contours, as illustrated in figure 4.3.

Furthermore, as Kass *et al.* (1988) demonstrate, the snake algorithm can serve to track the stereo match of two graphs, by supplementing the existing Snake with a certain additional energy function. In another demonstration, with another additional energy function it can track slow motion such as the movements of lips, specifically with the rate of eight frames within two seconds (Kass *et al.* 1988, p. 329).

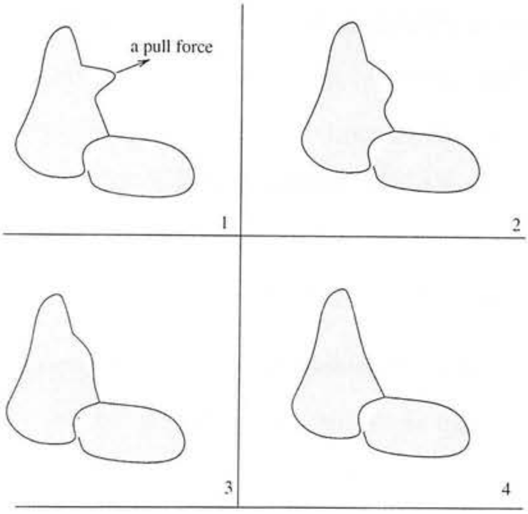

Figure 4.2: **The Interaction between an Image (in Particular, an Edge) and an External Force.** The series of four graphs show two snakes, one with the shape of a pear and the other with shape of a potato. Upper-left: the pear snake is pulled by the user away from the original edge. From 2 to 4, we can see the effect of shape change after the user let go of the snake: the snake gradually returns to its original position. Re-drawn with configuration from Kass *et al.* (1988), figure 3, p. 325.

As indicated above, the power of Snake is demonstrated in the tracking of interactive specification of image contours. Because of its capabilities of balancing different forces (such as edge, external pulling force, internal continuity, binocular images, and motion), Snake can perform the tracking of objects, be they rigid or elastic, stationary or moving. The elegance played by the Snake is the expression of interactions between component forces in terms of addition.

By an additional energy function, Snake maintains the balance between various forces, and a local minimum will be eventually accomplished. Hence, when an additional energy function is incorporated, the resulting snake algorithm is capable of determining a certain additional function, such as the tracking of motion and binocular match. The functionality of the snake algorithm, thus, can be realised in *incremental* snake algorithms. Based on the increment of energy functions in Snake, the processing of visual features can interact with higher levels of processing.

Snake is versatile in an epistemological sense in four ways. Firstly, it is a mechanical *module* but displays a certain extent of *flexibility*, because of the internal continuity of a spline. An irregular shape can be *firmly and regularly* tracked on the basis of different types of images (such as line, edge and termination point), and simultaneously be *smoothly linked* because of the force of internal continuity. Thus, the modularity of a capability does not cause the lack of adaptiveness, and the flexibility does not lead to the deficiency of regular forms.

Secondly, Snake appears to be an algorithm with the capability of *universal* shapes and *indefinite* levels of processing, but each module of a certain visual processing, such as edge or motion, needs to be characterised by pre-formed knowledge with regard to that *particular* feature. As a consequence, the snake algorithm can be highly adaptive to a variety of visual features at different levels of processing (e.g. edge, line, subjective contour, binocular matching, and motion), with good interactions between those features. The characterisation of pre-formed knowledge does not prevent the tracking contour displayed by Snake from integrating smoothly different visual features.

Thirdly, the processing at different levels of organisation (such as edge, binocular match, and subjective contour) is not necessarily sequential in temporal order, but is integrated in parallel. The interaction of processes across different levels of organisation can thus be synchronised.

Lastly, although Snake claims to offer active vision (Kass *et al.* 1988, p. 322), it is not in itself sufficiently so, without further support, such as by the Kalman filter (see below).

If Snake is to be seen as an active system it is straightforward to ask about its required tasks, which relate to the perceptual guidance it provides (by the selection of perceptual information) in support of certain bodily actions. Like other systems of visual tracking discussed later, Snake maintains smooth links between basic perceptual images with the effect of generating smoothly and flexibly integrated contours, which are significantly informative guidance of tracking and further bodily actions such as catching and hunting. The task of Snake is to provide those integral contours in real-time response.

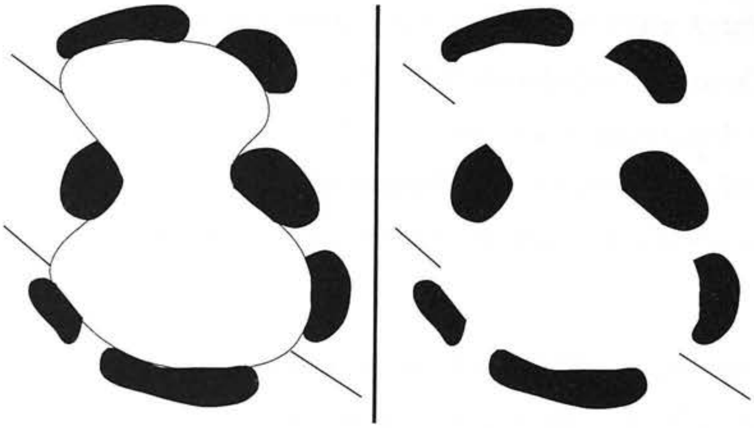

Figure 4.3: **An Example of Tracking Subjective Contour Illusion.** Right: the standard subjective contour illusion. Left: The tracking of the subjective contour by the Edge/termination snake. Redrawn with configuration from figure 5, Kass *et al.* (1988), p. 327.

Further on the negative side, the snake algorithm will be downplayed to a certain extent when we have further epistemological considerations about its robustness and self-sufficiency. The determination of a local minimum is not sufficiently robust, for it is over-sensitive to noise. In addition, Snake tends to be less adaptive than expected, when motion and shape-changing of the tracked target are fast. To improve the snake algorithm in the above two regards (noise and speed), the snake algorithm needs two supplementary algorithms – the Kalman filter and dynamical systems.

4.1.2 Kalman Filter

The Kalman filter is a linear algorithm introduced by Gelb (1974) to filter out various types of noise with a view to obtaining from measurement an expected value a of the target object. A general form of the Kalman filter algorithm is as follows:

$$\hat{a}_k = \hat{a}_{k-1} + K_k q \tag{4.3}$$

where $\hat{a}_k$ is a vector expressing the kth estimate of the expected state vector a (e.g. an elastic shape), q is the *innovation* vector (new information detected at the $\hat{a}_k$ estimate), and K_k is the *Kalman gain* (or knowledge gain – the gain matrix expressing the 'propositionality factor') (Haykin 1995; Ayache 1991, p. 178). Note that the estimation is computed *recursively* on the basis of a previous estimate $\hat{a}_{k-1}$ and the innovation q. Also note that the value $\hat{a}$ may be ultimately nonlinear, while the Kalman filter is basically a linear equation. Because of its linearity, the Kalman filter serve as a convenient tool to *approximate* nonlinear values (Ayache 1991).

Note that a particular instance of the Kalman filter presumes particular knowledge of limited areas, as reported by Haykin (1995) (in Arbib (1995) (ed.), p. 83). Perceptual inputs are consequently transformed into perceptual features which are relevant to the current situations.

The filtering out of noise and the tracking of fast-moving objects, presumably, will improve the adaptability of the mechanism subserved by the Kalman filter. However, the Kalman filter algorithm has its limitations, which must be rectified by specific technical improvements. Some of these are:

1. Iterated Kalman Filter: For Reducing Error. The linear approximation provided by the Kalman filter is no longer accurate once an estimate $\hat{a}_i$ has already gone too far away from the expected value a, which may be nonlinear. This problem can be obviated by the *iterated* Kalman filter, where the incremented error is adjusted to the error of the earliest estimate, with the following details. The recursive process is initiated by $\hat{a}_0$ (an *a priori estimate*) and S_0 (the *covariance matrix* associated with the error in the estimate). For a later step of the recursive process, the covariance matrix S_k associated with the error in the estimate becomes incrementally higher, and consequently the approximation becomes farther and farther away from accuracy. Re-initiating the recursive process of the Kalman filter, by adjusting the covariance matrix S_k to S_0, would reduce the incremented error and hence bring the recursive process closer to the expected accuracy (Ayache 1991).

2. Adaptive Kalman Filter: For Catching an Evolving Target. In the above discussion the target tracked by the Kalman filter is assumed to be stationary; that is, the expected value a is assumed to be constant. However, the target of tracking may be itself evolving, e.g. by elastic deformations, or through the kinematics of certain motions. This problem can be recovered mathematically by incorporating into each iteration of the iterated Kalman filter a Gauss-Markov equation (for details, see Ayache 1991, pp. 186-187). The key mathematical equations that implement the dynamical Kalman filter will be listed below, in order to show that dynamical systems really apply to the Kalman filter, and that those dynamical equations (as the mathematical forms indicate) indeed stem from the general form of The Kalman filter algorithm ((4.3)) as it extension.

As an alternative to the Gauss-Markov equation, the algorithms of dynamical systems theory can be incorporated into the Kalman filter, which leads to a different kind of adaptive Kalman filter. This is done by first establishing a *continuous Kalman filter*, which assumes a systems model:

$$\frac{d}{dtu} = Fu + q \tag{4.4}$$

where F is the system matrix, u is the abbreviation of state variable $u(t)$ (the previous a), and q is a white Gaussian noise process with covariance Q (for details, see Terzopoulos and Szeliski (1992), p. 15-16).

Then, transform the equation 4.3 into the formation of dynamical systems, as follows:

$$\dot{\hat{u}} = F\hat{u} + S^{-1}H^{\top}R^{-1}(d - H\hat{u}) \tag{4.5}$$

where $S^{-1}H^{\top}R^{-1}$ is the Kalman filter gain matrix (for details, see Terzopoulos and Szeliski (1992), pp. 15-16), and $(d - H\hat{u})$ is the residual error (i.e. the innovation). In addition, the covariance matrix S, together with its coupling with the Kalman filter gain matrix $H^{\top}R^{-1}H$, can be updated over time (see Terzopoulos and Szeliski (1992)[1], pp. 15-16):

$$\hat{S} = -SF - F^{\top}S - SQS + H^{\top}R^{-1}H. \tag{4.6}$$

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[1] Terzopoulos and Szeliski (1992) state that equation (4.6) is derived from the standard matrix Riccati equation from Gelb (1974), p. 122, using simple matrix algebra.

The resulting dynamical Kalman filter is far more flexible than the Kalman filter in the form of (4.3), because it has incorporated the capability of the dynamical systems. Notice that the mechanism of dynamical systems, like the snake algorithm, is a highly adaptive module.

3. Kalman Snake. Terzopoulos and Szeliski (1992) integrate a Snake with the Kalman filter by identifying the system model of the continuous Kalman filter in the equation (4.4) with a snake model of motion. Such a design takes advantage of the aforementioned dynamical Kalman filter, because their snake model of motion is put in the form of Lagrangian dynamics, an equation of dynamical systems (for details, see Terzopoulos and Szeliski (1992), pp. 5-18). The resulting Kalman filter is then presenting the characters of both the dynamical Kalman filter and Snake.

4.1.3 Dynamical Templates

Taking Advantage of Templates. Templates are presumably helpful for tracking when the sensory inputs and the stored templates match closely. As an example – tracking a dish with edges and corners, the dynamical contour tracking along the flow of edges *and* corners; when more assumptions are added, the tracking performance neatly attaches *only* to the edges, one after another (Curwen and Blake 1992, p. 45). The problem is that the sensory inputs are usually distracted by certain factors, such as foreshortened length or different lighting conditions (Yuille and Hallinan 1992). The following discussion shows that the application of templates is not stringently limited, because between templates there can be fine tuning. Even if there is noise, which leads to uncertainty, templates can be supported with a Kalman filter to filter out noise. As a consequence, the problem is to ensure the *flexibility* of the fine tuning between the parameters of the templates.

Lagrangian dynamics. As mentioned previously, a pre-requisite (though not stated in definition) of active perception system is to perform the required task in *real-time*, on the one hand, and to *ensure the accuracy* of perceptual judgement in the changing environment in support of the required task, on the other. These two poles of the same requisite seem to be heading toward different directions, and hence become a challenge to the modelling of active perception.

An expedient resolution of the above two poles in the same model is to apply *dynamical templates* to the imaging inputs in support of the tracking of the consequent contour. Being templates, they provide *prior assumptions* to catch *expediently* the unclear imaging inputs with certain accuracy. The contour would consequently be 'frozen' in the form of a given template. Being dynamical, those templates respond to a number of parameters of the changing imaging inputs, by combining such parameters interdependently in terms of dynamical systems theory, as evident in Lagrangian formulation. Such parameters can be exploited by '*modal analysis*' of geometrical contours, in consideration of the properties of contour in motion, such as various properties of rigid translation, elasticity and viscosity of geometrical contours in motion, (Curwen and Blake 1992, pp. 46-52). The modal analysis gives rise to a variety of modes (i.e. parameters), as illustrated in figure 4.1. Such modes demonstrate the possible configurations of simple splines, in association with different respective eigenvalues and eigenvectors.

In the context of Lagrangian dynamics, the aforementioned parameters are viewed as independent 'second order' control systems, each of which determines how the template is *relaxed* (i.e. a fixed value is replaced by a variable) with respect to a certain parameter in view of higher accuracy of tracking (Curwen and Blake 1992, pp. 40, 45-46). A tracking task may take advantage of the tuning across parameters, and consequently constrains the tracking performance effectively and efficiently.

Note that such parameters are interdependent in the Lagrangian formulation, a model of dynamical systems. The *stable* states of the deformable contour can be derived from the equilibrium states of the Lagrangian dynamics, where those parameters serve as controlling forces in response to the influences of the changing environment. In addition, grounded on the dynamics of those parameters (i.e. tight coupling of those parameters under the control of differential equations), the deformable contour may well serve to predict the contour of tracking, with regard to either the changing contour within a single template, or the gradient across templates (pp. 46, 48). The activity of tracking, thus, not only responds swiftly to catch the imaging inputs, but also settles flexibly on certain equilibrial states with relatively high accuracy. As a consequence, dynamical systems modelling takes a role in the design of dynamic tracking, in relation to the effectiveness and efficiency of the tracking contour and its trajectories within or across general templates.

Also note that the recognition of a deformable contour is not supported by the reconstruction based on hierarchical processes, but by the self-organisation of systems dynamics. There are no built-in modules of information extraction. Systems dynamics facilitates the effective recognition of deformable contours in real-time. Although the systems dynamics does not in itself lead to iterative requests for further perceptual information for performing the required task (which we do find in gaze control), it can be seen as an important component in active perception because of its *generic* mechanism for feature generation and its effective response in real-time.

Lagrangian Template cf. Snake. The adoption of templates (i.e. prior knowledge) facilitates tracking significantly. The snake algorithm has a lower rate of effectiveness and efficiency if not supported by prior knowledge. When the source of stimuli is switched off, Snake loses its shape, if no further support is available from a Kalman filter (Terzopoulos and Szeliski 1992, pp. 19-20), which presumes certain amount of priori knowledge (Haykin 1995). In general, templates lead the tracking contour to certain fixed tracks when no sufficient information is gained. The contour is 'stiffened' by coupling its shape to a template spline (Curwen and Blake 1992, p. 50), while those without support from templates would have no available track to follow. Furthermore, the template adopted in the Lagrangian dynamics constitutes a firm ground for fine tuning of various parameters pertaining to the template, which leads to effectiveness and efficiency of tracking.

In this regard, Snake, even when supported by the Kalman filter, has no way of capturing rapidly evolving objects efficiently. According to what we mentioned previously, a Kalman filter presumes certain prior knowledge for *filtering out noise*, but this is not tantamount to a capability of *searching for close contours.* The prior knowledge embedded in the Kalman filter does not serve to suggest evolving shapes, except insofar as this results from the support of dynamical systems, which *provide* the tight coupling of shape parameters[2].

Dynamical contours on the basis of Lagrangian templates are similar to Snake, in the sense that both of them can be incorporated into Kalman filter, where uncertainty can be reduced significantly. Yet, dynamical contours, despite their use on templates, work more flexibly than Snake. Flexibility, in fact can be achieved significantly by the fine tuning of parameters. This is because the dynamical coupling of contours provides a firm basis for fine tuning across modes/shapes, be they (contours) performing within or across single templates. The dynamical contours consequently gain control over motion effectively. Specifically, they provide flexible control with regard to the properties of rigid translation, elasticity and viscosity (Curwen and Blake 1992, pp. 40, 47).

By contrast, Snake can only take account of forces, external or internal, that affect the adoption of shape components (e.g. edge, line, termination point) and the internal continuity between those components. Without the aid of templates, the tracking begins from scratch. No contours are made available to support tracking, let along the fine tuning between various modes/shapes (of contours) supported by dynamical template. In brief, Snake is less effective and efficient in tracking than dynamical contours.

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[2] It is unclear as to whether a Snake supported by an adaptive Kalman filter performs equal to the Lagrangian dynamical contour, which can be further supported with Kalman filter, too. To evaluate the performance of tracking mechanisms with various types of hybrid needs direct experimental evidence over the hybrid types.

4.2 Planning of Tracking Procedures.

Planning is a core topic in traditional AI. However, it is not its exclusive privilege. As we will see in the following discussions, oculomotor activities require the planning of an agent's motion; and this planning is active. The reasons are that the planning task is carried out in real-time on the basis of continual organism-environment interactions, and that the agent moves to exploit the *unmodelled* environment in support of a planning task which is satisfactory on account of its motor performance. In the following discussions we will see two models of planning in support of active vision – Adept (a robot) and Dickmanns' car.

4.2.1 Adept – Detecting Obstacles and Moving Forward Through Free-space

Gaze control, as an autonomous system, not only subserves the tracking of single objects, as we have seen, but also serves to avoid obstacles and then guides an agent to move along through the free-space between objects/obstacles for facilitating robot's travelling. The latter capability is demonstrated by Adept, a mobile robot designed by Blake *et al.* (1992). It can detect un-modelled obstacles standing in the environment and pass over them with the effect[3] of reaching a pre-specified goal, and return to the its starting point. Note that the task of reaching a goal by passing over obstacles beforehand is more challenging than the task of simply avoiding an obstacle. Although the goal is pre-specified, it lies behind certain obstacles in an unpredictable environment. A robot, as guided by its visual system, may successfully avoid a particular obstacle by a swift movement of withdrawal but consequently collide with another obstacle (see Section 4.2.1, page 126). When the mobile robot encounters certain obstacles, it must avoid them *and* simultaneously *ensure* a free-space to traverse. Such considerations circumscribe the task of motion planning for Adept.

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[3] As is seen from its capabilities, Adept may *look as if* that it *intends* to reach the pre-specified goal. To highlight the functionality of its autonomous mechanism, the term 'with the effect of' appears to be more neutral, for it implies non-intentional activities.

Adept is a visual system with a camera mounted on a movable arm. It identifies a free-space by (1) detecting from a certain vantage point the surface shape of an encountered obstacle (i.e. a rigid object), (2) determining the *sideness* of that shape – which side is free-space and so navigable, and then (3) managing to determine from various vantage points the range of this free-space – the free-space confined by the extremal boundary of another obstacle. With such a free-space identified, it is then straightforward for a robot to pass over the unmodelled obstacles, to 'conquer' other obstacles, and eventually to reach the pre-specified goal.

Detecting the Surface Shape of an Encountered Rigid Body from a certain vantage point. The free-space circumscribed by rigid bodies may be close to that needed, hence their surface shapes are critical for the success of passing through. The shape may not always be as simple as a plane, but may very likely be curvy to various degrees[4]. The surface shape of a rigid body, as viewed from a moving camera along a certain horizontal plane, can be determined in two main steps (see the detailed technical discussions in Blake *et al.* (1992), pp. 176-181).

First, Adept computes certain useful values for the four critical variables – (i) the unit vector $\mathbf{T}$ viewed from a certain vantage point that is directed to a given point $\mathbf{r}$ on the surface, (ii) the curve normal $\mathbf{N}$ of the surface viewed from the above vantage point, (iii) the normal curvature κ_n, and the geodesic torsion τ_g. In the second step Adept computes the geodesic path of the surface, with its one end connecting to the camera (i.e. the surface sensor), on the one hand, and the other end connecting to the goal, on the other. Given the above four values, as indicated by Blake *et al.* (1992), a *unique* geodesic path would be determined. The importance of this geodesic path is that it determines a curve section of a

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[4] As an extreme condition, the surface of a cylinder may be taken as a particular case of a curvy surface – with the curvature of zero degree. Similarly, a plane surface is a surface with the geodesic torsion (see later discussions) of zero degree. In addition, the curve normal $\mathbf{N}$ of the given point $\mathbf{r}$ is the degree of curvature of the envisaged surface at the point $\mathbf{r}$, expressed as a vector perpendicular to the surface. The normal curvature κ_n refers to the curvature of the curve-section on the plane determined by $\mathbf{T}$ and $\mathbf{N}$. The geodesic torsion τ_g is the degree of torsion of the would-be geodesic section that connects to both the camera and the goal.

parallel surface along which the agent can move in order to avoid the rigid body (i.e. the obstacle).

It is worth noting that the *design* of Adept uses differential geometry in the computation of the above four values. No tightly coupled differential equations are adopted. Like the finite state machine in Brooks (1986, 1991a), such as the simple automaton *wander* of the robot Allen, the determination of a geodesic path constitutes a baseline of Adept's architectures.

Determining the *Sideness* of Surface Shape by Scanning Horizontally. The visual system of Adept determines the sideness of an obstacle on the basis of two subgoals. First, lock the gaze on the *obstacle*, which must be a close body with certain mutually convergent contours. This is done by a dynamic contour tracker, as mentioned previously in the discussion of tracking (see Section 4.1.3, page 122). Because the subgoal of this stage is to direct the gaze toward an object, not to depict its accurate contour, a tracker running at coarse scale would suffice. For the second subgoal, Adept exploits the locked area by *scanning it horizontally* at a fine scale with the dynamic contour tracker, in an attempt to work out the estimated normal curvature κ_n. Blake *et al.* (1992) must presume that an obstacle has a 'non-concave' shape[5]. With this presumption, the value of normal curvature κ_n can serve to identify the non-concave part of the fixated target, which is presumed to be the obstacle. In this horizontal plane, the internal side[6] of the non-concave area, either at the right-hand side or at the left-hand side of the horizontal plane, can be identified as the position where the obstacle rests. Note that no properties of rigidity are taken into account. This is not a proprioceptive system, but a visual system.[7]

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[5] As admitted in the exposition of their Figure 11.4, Blake *et al.* (1992) put the consideration of geodesic path in the context of non-concave obstacle (p. 179).

[6] The horizontal scan should be maintained broadly, for an obstacle may have a *locally* concave area surrounded by convex areas, as showed in Figure 4.4. Such a consideration, however, is not reported in Blake *et al.* (1992), but it must not be left out, for a successful identification of single obstacles.

[7] The mixture of proprioceptive and visual information may be the way in which biological organisms undertake to identify obstacles. This is because additional perceptual modalities are likely to facilitate the identification of object properties.

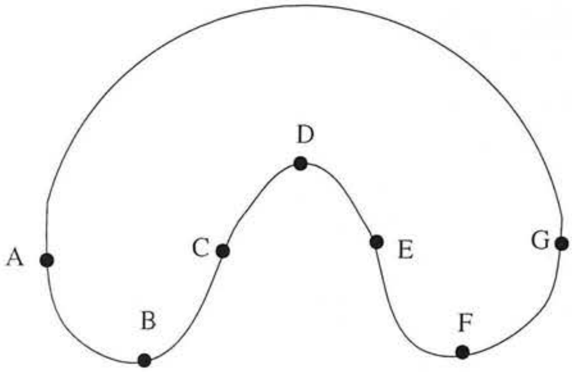

Figure 4.4: **An Obstacle Encountered by Adept.** An obstacle may have a *locally* concave area surrounded by two convex areas.

Crudely speaking, Adept is an *active* visual system, for the property of sideness is neither pre-determined nor selective from various readily available possibilities. Rather, such a property is determined gradually by the exploitation of motor activities (i.e. scanning horizontally), which make available the needed information (the sideness, at this stage) for the required task – passing through obstacles and getting the target object back.

Determining a Free-space. Now, Adept stands in a position to identify the free-space between obstacles, so that it can pass through the free-space to reach the pre-determined goal. The question is how to determine which obstacle is the nearest one ready to pass through. Furthermore, although the sideness of one obstacle has already been identified, the free-space is yet to be determined. The present task is to pass through free-space across unmodelled obstacles and reach the distant object. For the robot to reach the distant goal, such a task involves *several cycles* of the following three component activities: determining sideness of single obstacles[8]; (from a particular viewpoint) ensuring a free-space and passing

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[8] Blake *et al.* (1992) regard the previous motor activities, which lead to the determination of sideness of single obstacles, as *explanatory motion*, without explaining why it is explanatory. At least, they need to state what those activities explain, and how they explain. Note that Churchland (*et al.* 1994) also take saccadic movements as being predictive and explanatory. Possibly, this is a general character of active vision, as characterised previously (BC1) (see Section 3.2.4, page 86). Such motor activities must be highly selective and useful for the required task. This needs to explain, as to what is needed and how they support the required task. Thus, it is not difficult to make sense of the *explanatory* motion, which can be accordingly taken as a general character of active vision.

through it; and moving to a new viewpoint for the next observation.

Given that the first of the three components has been described previously, now Adept needs to work out a free-space beside the side (i.e. an extremal boundary of an obstacle) already detected. The robot moves to detect the other side of the free-space, which is an extremal boundary of another obstacle. To ensure that the area between these two sides is really a free-space, the mobile robot is required to ensure that there is no further obstacle standing in between those two sides.

Notice that the robot need not strive to detect the extremal boundary of a side until it ensures that there is no *nearer* would-be obstacle. That is, Adept needs to identify the nearest obstacle before its extremal boundary is specifically depicted. This can be done by the robot motion approaching the detected target. That target can be recognised as the *nearest* obstacle, if the robot motion approaching closely to it does not trigger an occlusion event (figure 4.5). An occluding feature, as Blake *et al.* (1992) point out (pp. 183-184), can be detected by the Kalman filter discussed in Rao (1992) and Bar-Shalom & Fortmann (1988). Whenever an occlusion event turns up, there must be a nearer obstacle, and Adept needs to swift its gaze on it to ensure that there is no further nearer obstacle standing in between. When the nearest obstacle is eventually determined, Adept can move to exploit its extremal boundary, by determining the sideness discussed previously. As a consequence, a free-space between two obstacles is determined. With this information, Adept quickly passes through. Later, it works out another free-space in its way to the goal, and passes through. By repetitive processes of passing through a free-space, the mobile robot will eventually reach the goal.

Of course, the environment of Adept may be changing, where obstacles may move. The computation of free-space therefore must be responding quickly in real-time. Adept is promising in this regard, because exploitation of its motor activities is limited to useful information step by step, for the required task. This is a basic requirement of the active vision approach. The mobile robot accordingly

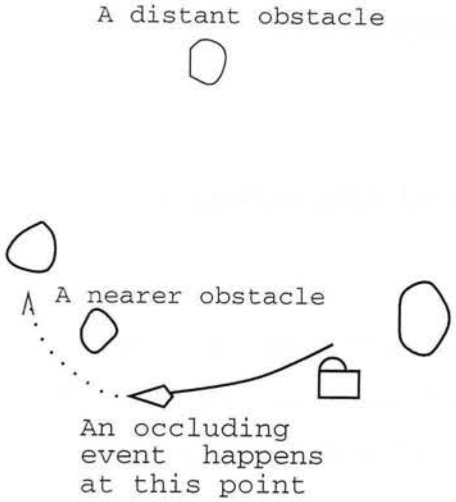

Figure 4.5: **An Occlusion Event.** When a robot (Adept) holds its 'gaze' on the target and moves around, an interposed object/obstacle would incur an occlusion. This is termed an *occlusion event.* If the robot approaches closely to an object without triggering an occlusion event, it thereby can recognise that between it and this object there are no obstacles.

looks *adaptive* to the changing environment.

If, unfortunately, Adept moves to a certain narrow free-space which is too narrow for it to pass through, or simply moves to a dead end, then it is trapped there. It must backtrack to a previous position.

The mobile robot needs to move back. Even if it has never been thus trapped, Adept's task requires it to move back to its starting point eventually. This is important for navigation, in order to identify the *home* of navigation. As Blake *et al.* (1992) indicate (p. 183), this can be done by learning its location, from the beginning of exploiting the free-space, using the 'Epipolar Plane Image' (EPI) explored in Bolles *et al.* (1987).

Summary. To summarise, Adept can pass through obstacles, execute a planning task to reach a goal in real-time, and move back, by its motor motion toward a single obstacle to exploit its extremal boundary, and by working out the free-space between the two nearest obstacles. Note that the planning task is gradually accomplished during the mobile robot moves to exploit the spatial properties of an extremal boundary and a free-space, and during the system learns the locations of itself and the obstacles.

4.2.2 Dickmanns' Car – Navigation with Dynamical Scene Understanding

Scene understanding is important for navigation, because a vehicle needs to identify traffic lanes, edges to the road, surface conditions, other vehicles, and obstacles. Identification of such objects is different from, but presumes, the process of active already discussed. Previously we dealt with sensory processes. They conform to the notion of active vision raised by Ballard (1991), where the active process serves to make available the visual information needed for the visual tasks. By contrast, visual understanding is a high-level process, relating to perceptual recognition. Despite such a difference in levels, the visual processes remain active, in the sense that processes at different levels interact, and these visual processes still subserve motor activities, e.g. navigation. Active vision in this sense conforms to the notion of *interactive* vision advocated by Churchland *et al.* (1994).

Dickmanns (1992) presents a combinatory approach to navigation – *the 4-D approach to dynamic machine vision*, which is supported by multiple processes of active vision. The task is the navigation of an autonomous car. His car plays a variety of traffic skills, including lane keeping on road, speed adjustment to road curvature, driving at night, detecting obstacles, stopping in front of an obstacle, convoying (driving behind another vehicle), stop-and-go behind a preceding vehicle, and the lane changes triggered by a human operator in order to avoid other vehicles in the neighbouring lanes. As we will see, Dickmanns' car involves active vision in both the senses of Ballard's and Churchland *et al.*'s.

Dickmanns' Strategy of Information Processing – *a priori* Knowledge as Constraint. How is his autonomous car capable of playing those traffic skills? The basic idea of Dickmanns' is a combination of parallel models, parallel processes, and the interaction of signal inputs and internal models. The models comprise feature extraction, road recognition, obstacle recognition, controlling geometric position, identifying lateral vehicle states, and the control of ego-motion. Despite the complicated combination, what makes his vehicle active is only the third component – the interaction of signal inputs and internal models. Dickmanns sees signal inputs as being dealt with by 'signal driven' processes and internal models as being maintained by 'model driven' processes (Dickmanns 1992, p. 314).

As mentioned in Sections 2.7 and 3.2 (page 73 and 81), active processes are not necessarily incompatible with reconstructionist processes. One possibility of their compatibility is to circumscribe active vision to early processes; thereby, the early vision makes available needed information for the higher level processing, which is maintained by passive vision. Dickmanns' approach is different: the signal driven processes provide certain *candidates* for visual recognition and the model driven processes *constrain* them recursively, until a best solution is achieved. Without adopting those model driven processes, the visual processes would become purely reconstructionist, and it would then be difficult to maintain the recognition tasks in real-time.

What those model driven processes provide is the *a priori* knowledge encoded in the models, namely the *spatial invariance* of rigid objects with regard to their 3-D shapes, and 'the *temporal continuity* conditions in finite motion processes for specific task domains' (p. 309, italics added). As Dickmanns views it – the spatial invariance as 'laws of perspective projection' and the temporal continuity as the 'Gestalt' property of moving objects – the *a priori* knowledge is not seen as passive knowledge to be explored, but as active constraints which serve to reduce the workload of computation, as laws and gestalt properties usually do for the economy of cognitive processing. As Dickmanns admits, these two components of *a priori* knowledge ground his 4-D approach to the scene understanding in navigation (p. 309).

The contribution of such *a priori* knowledge to machine vision can be conceived (as Dickmanns indicates) in the context of Extended Kalman Filters (EKF) (Maybeck 1979), an extended version of Kalman filter for non-linear systems. Such *a priori* knowledge qualifies Dickmanns' 4-*D* approach as a further extension of the EKF. As he explains, the Kalman filter algorithm in general deals with measurement under noise recursively, in order to obtain the best estimates of dynamic behaviours in the visual scene, and thereby introduces useful knowledge about those dynamic behaviours. By contrast, his 4-*D* approach, by adopting 3-*D* shape properties and the motion constraints provided by *dynamical*[9] models, not only does this but also *utilises* the EKF with the *continual* conditions of the spatio-temporally represented objects in 3-*D* space and time.

Modifying Hypotheses with the Constraints Maintained by Dynamical Systems. The role of the *a priori* knowledge, as we mentioned previously, is to provide *constraints* over the candidate hypotheses of object states that are derived from signal inputs. What is worth noting is the tight coupling of parameters in a dynamical model, say a model of obstacles (of which the shapes may be detected as being changing when a car is moving), during the vehicle training in the road environment. The training process leads to the instantiated values feeding forward to those parameters (of the candidate object hypotheses). Like the generation of deformable contours on the basis of dynamical models (see Section 4.1.3, page 122), the dynamical constraints of parameters in object hypotheses are effective in *real-time* control. In addition, the tight coupling of parameters may be supported by different dynamical models, which are tantamount to different trajectories of moving objects (obstacles, specifically), until salient outcomes of object hypothesis are derived. As Dickmanns indicates, modification is firstly maintained over the parameters in object hypotheses. If the prediction errors of object hypotheses remain large, then those hypotheses will be adjusted by relating to different dynamical models, which manifest different trajectories

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[9] Note the two similar terms in this paragraph – 'dynamic' and 'dynamical'. Note that the present thesis treats them differently: the former refers to any dynamics, while the latter is reserved for dynamical systems, as characterised by dynamic systems theory, be they stochastic or not. Regarding the first term – 'dynamic' – the Kalman filter is a linear process, which consequently does not presuppose dynamic systems theory. Regarding the second term – 'dynamical' – Dickmanns specifically adopts the dynamic systems theory in his 4-*D* approach to navigation.

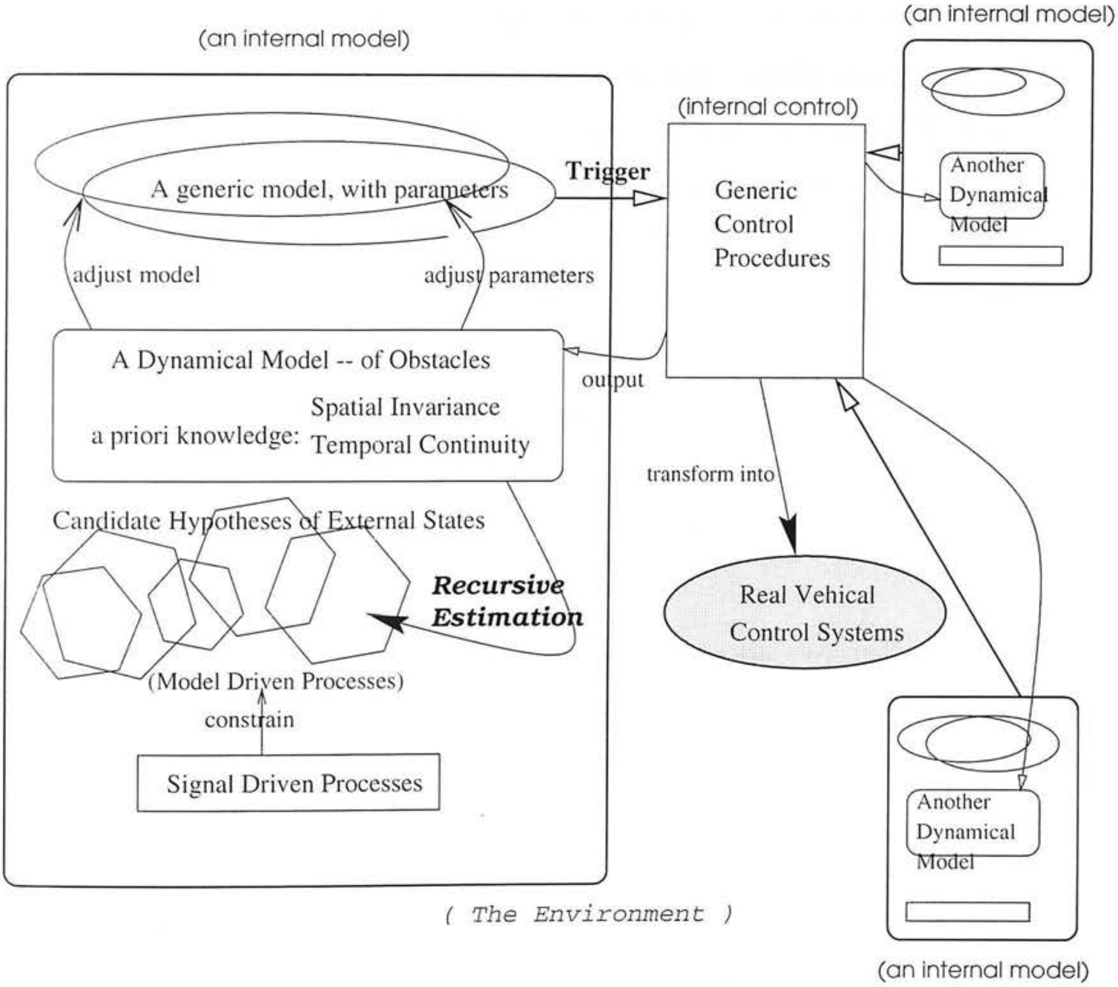

Figure 4.6: **Dickmanns' Car, Controlled by Parallel Dynamical Models.** The architectures of Dickmanns' car consist of various tracking sub-systems. Each sub-system is a dynamical system, with its parameters and the generic model of the sub-system being modifiable. The processes of these tracking sub-systems are arranged by generic control procedures.

of moving obstacles. Accordingly, this implementation is indeed an autonomous design sensitive period by a variety of dynamical systems.

The performance of Dickmanns' car is facilitated by the *parallel* dynamical models, which are separately operating under *real-time* constraints. The performance would not have been successful, yet, if it is not the feedback or feed forward controls which transform the respective measures of the aforementioned dynamical models into *generic* control procedures, such as lane keeping (by feedback control) or lane change (by feed forward control). All generic controls are outputted to both the real vehicle systems and the aforementioned dynamical models. The outputs to the dynamical models, understandably, serve to provide updated information of car motion to update those models.

To summarise, the successful performance of Dickmanns' car is maintained by (1) the recursive estimation made respectively by parallel dynamical models, and (2) generic (real car) control procedures which are outputted to those dynamical models.

Without any action being predetermined, Dickmanns' car eventually *becomes capable of* navigating safely in real road environment with real-time response, with the aforementioned traffic skills being demonstrated. This is, apparently an instance of emergence.

Two Senses of Active Processes. Note that the emergence is brought about by the dynamical models tightly coupled with spatial (3-D) *invariance* of rigid objects and the temporal *continuity* of moving objects. Those dynamical models lead to active processes in two senses, as follows.

On the one hand, the ego-motion of the car makes available the moving conditions in the scene, which *initiate* the aforementioned various dynamical models with the effect of facilitating (by providing additional constraints) the signal-driven object hypotheses, in support of scene understanding. The active vision in this sense conforms to Ballard (1991), who focuses on the sensorimotor activities which make available the needed information for the required task.

On the other, there is interaction across levels of processing, in that the signal driven processes provide certain candidates for visual recognition and the model driven processes constrain them recursively until a best resolution is gained. Such visual processes eventually support the motor activities of navigation. The active vision in this sense conforms to Churchland *et al.* (1994), who highlight the interaction across levels and behaviour-based vision.

The emergence supported by active vision in these two senses is intriguing, because this strategy of emergence supports a new paradigm of emergence, as we will discuss in Part III (chapters five to seven).

4.2.3 The Role of Prior Knowledge in Tracking Deformable Contours and Navigation

For an organism, a real-time response to various environmental challenges, which normally needs to be quick, can be facilitated by making available *pertinent prior knowledge* of *its* environment. Indeed, such knowledge can be seen as a characteristic of the organism's ecological niche. The environment will remain roughly the same throughout generations. Freshwater fish, for example, need not be equipped with the salt filter system which is instead required for marine fish.[10] A prey will be permanently alert with regard to a particular type of predators, by taking special notice on certain perceptual cues in the environment which signal the predators' approaching.

The pertinent prior knowledge of a particular species can be seen by its surface value as an *instinct*. The question is where such pertinent prior knowledge resides in the organisms. It seems to be a matter of interpretation and evaluation, rather than a particular property of sensors (Habert and Purski 1997). In consideration of navigation, such pertinent prior knowledge may be seen as being virtually a map. Provided that such a map is readily available, a quick

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[10] Freshwater fish are *not* equipped with the salt filter system. By contrast, such a system is indeed required for marine fish (Ruppert and Barnes 1994).

and accurate response can be derived on the basis of incremental observations and modifications, as Habert and Purski (1997) demonstrate. They show that the in-built pertinent prior knowledge in an autonomous navigation system can be modified by reducing the encountered uncertainties or by altering planned activities in real-time.

In their design, a point is worth noting in relation to active vision. Apart from the pertinent prior knowledge, *no hierarchical internal processes* are required. That is to say, daily activities on the basis of the pertinent prior knowledge suffice to refine such knowledge, with the effect of increasing adaptiveness to the environment. Note that the *prior* knowledge of a species does not impede, but increases, its adaptability to the changing environment. Modularity and adaptability turn out not to be subject to a trade-off relation. Hence, the pertinent prior knowledge can be seen as a good facility in support of active vision in the task of navigation. The needed information for the task of navigation can be gradually *incorporated into* the navigating robot, in the form of gradually modified pertinent prior knowledge.

As demonstrated in Curwen and Blake (1992) and Habert and Purski (1997), the adoption of prior knowledge can facilitate the implementation of active vision, for it does not impede but indeed increases the adaptability of robotic system in accomplishing their required tasks.

4.3 Summary

Tracking Two implementations of active tracking systems are discussed – Snake (algorithm) and the dynamical Kalman filter – the latter of which is exemplified by Dickmanns' car, a system consisting of several sub-systems for tracking different features. All sub-systems are dynamical Kalman filters (hence active) with between-(sub-)systems cooperation. Discussion of such systems points to intensive explorative processes. The tracking systems are active, for they move toward the targets to gather information, rapidly predict the trajectories and maintain the predictions iteratively. Different from gaze control, Snake and the dynamical Kalman filter presents clearer mechanisms of explorative control, as manifested in the energy control of Snake, the templates adopted in Dickmanns' car, and the flexibility maintained by dynamical systems.

The cooperation between the sub-systems of Dickmanns' car is grounded by the flexibility of single sub-systems. Notwithstanding, the global behaviour of Dickmanns' car goes beyond its component sub-systems. This is because the current circumstances of the generic control procedures are recursively fed back to each sub-system (a dynamical Kalman filter) with the capabilities of changing the predictions previously made in the sub-systems, by changing certain control parameters or even completely shifting to a new dynamical Kalman filter, which are all radical changes. The manifested cooperation, despite the possibility of radical change, is successfully maintained in real-time. The current state of each sub-system is dynamical, which is certainly not pre-categorised. As a consequence, the maintenance of cooperation can be seen as run-time planning, which is also not pre-categorised.

Run-time Planning The run-time planning in searching for a *pre-specified goal/target* is an important property of active perception, which is implemented in Adept, as discussed in Section 4.2.1. Adept is a navigating system with its target surrounded by random obstacles. The performance of Adept can be seen as visual planning because the path of navigation is entirely guided by visual mechanisms, which work out a route toward the target across obstacles, by stepwise computation of the relevant features of obstacles in relation to the target, and identification of the free-space sufficient for navigation. The analysis of Adept's architecture highlights the stepwise determination of the most relevant *critical variables* for figuring out a navigable path. The determination of those control variables manifests a serial order, in which each step of navigation leads to the nearest route toward the envisaged target. Because of the computation for working out such a route, Adept qualifies as a system of visual planning.

Part III

Discussions

Chapter 5

The Exploitative Control of Active Perception Systems

The topic of this chapter is the nature of internal control in active perception systems. Many questions need to be resolved. The discussion will divide roughly in two, one part concerning systems, the other concerning modules.

The first three sections of the chapter discuss the nature of systems, and the following questions are asked. First, what are the *tasks* of active perception, in contrast to the tasks of other behaviour-based systems (discussed in Section 5.1)? Second, how are such tasks identified by active perception systems, which are *behaviour-based* systems without intentions (Section 5.2)? Third, how should the processes be arranged, i.e. what principles should govern the architecture of intra-system processes and the connections between sub-systems (Section 5.3)?

Later sections address the nature of *modules*. Analysis shows that the modules of active perception systems differ from other behaviour-based systems. Active perception systems consist of *quasi-functional modules* and *quasi-action modules* (abbreviated as 'quasi-form modules'). Centred around this understanding, consideration points to the relationship between activeness and the internal control of active perception. To elucidate this relationship we address two inquiries: first, how such quasi-form modules contribute to active perception (beyond autonomous agents in general); second, why the internal control of active perception needs to take shape in the form of quasi-form modules.

5.1 Tasks: Introductory Remarks

The epistemological issues in active perception research can be encapsulated by the following question: how can an autonomous agent respond to a required task by identifying certain goals which reflect the information required/needed for that task, and be capable of collecting such information successfully on the basis of autonomous machinery, as opposed to a vital force, or homunculus? That is, within this question, the environment sub-questions are: why is an autonomous agent capable of seeking the *remaining* information needed for a required task, how can it manage to schedule subgoals of perceptual exploration in support of that task, and how can it eventually accomplish the task?

A straightforward but unsatisfactory answer is that everything about task and goal be hand-set by the programmer, i.e. the designer. This is true for most research in behaviour-oriented agents, where a mobile robot or a simulation must be built up by designers. The task is identified in the designers' minds and the goals are assigned by them, be the goals cast implicitly or explicitly in the design. The programming of active perception presumes a designer, by necessity; however, active perception as a capacity of real organisms cannot.

Central Themes and Notions. Of central importance in *active* perception systems is that they be capable of identifying a required task, the derivation of goals (i.e. needed perceptual data), the achievement of those goals, and the subsequent derivation of further goals or subgoals, in support of the identified task. Ideally, this is accomplished in real-time by autonomous programming. It would be helpful for future behaviour-based research, if we could establish an epistemological point of view to see how such features can be accomplished. Discussions in the following two chapters respond to this request, specifically by introducing the notions of operation-specialist systems, quasi-form modules, dynamic small modules, internal cohesion, and inverse ecological niche.

Consideration of the above questions must begin with the following two explananda.

- **Task Identification.** Explaining the identification of tasks, specifically the *initiation* of appropriate processes leading to the envisaged tasks, on the basis of the limited Architectures of autonomous systems;
- **Process Arrangement.** Explaining the arrangement of internal processes in serial orders, specifically the *continuation* of processes with the serial orders leading to the envisaged tasks, (also) on the basis of the limited architectures of the implemented autonomous system.

These two explananda are discussed below.

First Explanandum: Whence Comes the Identification of Tasks and Goals? It is claimed in active perception research that perceiving (living) agents are active, and that the the active perception research successfully implements active perception systems. The former claim seems to be well grounded, given the evidence in cognitive neuroscience, such as the attentive control of saccades. The latter claim appears to be supported by the robotic implementations of active perception in real environments, and we have seen in the previous two chapters that many robotic *implementations* really gain active capabilities in various forms. However, there seems to be, as yet, no *explanation* as to how the tasks or goals can be identified on the basis of autonomous machinery, be those agents real organisms or behaviour-oriented robots. As yet, it remains too early to claim that autonomous machinery can serve to identify tasks and goals in the environment. It seems to be the programmer, not the mobile robot (here, the implemented behaviour-oriented agent), that *knows* where there is a need to satisfy.

Second explanandum: Whence Comes Arrangement of Processes for Collecting the Required Information. The second explanandum concerns the question of how active perception systems can schedule their stepwise activities to fetch the needed information for the required tasks. Scheduling activities seem to have a flavour of planning, which needs explanation on the basis of robotic architectures.

Although it is not the case that everything needed for a task is pre-programmed like a function in traditional AI, it is *partially* determined. On the one hand, the needed information is collected in the course of organism-environment interactions which are carried out by the behaviour-oriented agents depending on the contingent environmental circumstances and the somewhat contingent robot activities (see Hendriks-Jansen 1996). Exactly what information is needed to achieve the pre-programmed goals is contingent, on environmental circumstances. The behaviour-oriented agents will 'endeavour' to achieve their goals in the somewhat unpredictable environment. On the other, the algorithms are determined in the sense of 'innateness' criticised by Quartz (1993).

Quartz (1993) states that certain results of (neural) network programming are borne in the minds of programmers and realised by special-purpose algorithms. He consequently challenges the programmers of neural networks, that a constructive neural network should be capable of responding to the environment by the *modification* of previously built up networks. In other words, the constructive neural networks must be adaptive to the environment to a certain extent. In the implementations of active perception, the mobile robot (given a task pre-programmed by the designer) can hardly identify a need (for a required task) by the modification of certain predetermined robotic processes, i.e. by run-time 'reprogramming'. In fact, as reported by Maes (1995), this is generally a difficulty for the current implementation of behaviour-oriented agents (p. 151), which we previously termed the scaling-up difficulty (Section 2.4.4, page 50).

Insofar as we have surveyed, two exceptions in the implementation of active perception have been seen to be the attentive control of saccades and the dynamic Kalman filter. The attentive control of saccades determines the next important point to foveat by means of a comprehensive pre-attentive record of salient visual features, a record comprising an exhaustive survey and comparison. By contrast, the dynamic Kalman filter can cope with evolving target objects by Lagrangian dynamics, an instance of dynamical systems. Such success is by no means a rule, but an exception. Note that the exception is not really attribable to the behaviour-based approach; the credit must be in part attributed to the dynamical systems approach. The behaviour-based approach *per se* still suffers from the scaling-up problem identified in Maes (1995).

An important aspect of activeness is the shift of control between the various sub-systems, which are separately implemented in different behaviour-oriented research. If the shift of control is again manipulated by hand-set design, rather than programmed autonomously, then the implementation of activeness in this regard is also unsatisfactory. Fortunately, we have one convincing implementation of this aspect of activeness in Dickmanns' car, where the implementation of needed processes is controlled by dynamical systems (see 135). Whether the adoption of dynamical systems can lead to pervasive facilities to control various needs, however, remains an open question. It (the adoption of dynamical systems) may well be highly useful, but it remains unclear what kinds of dynamical process should be introduced to support a particular circumstance of behaviour-oriented agent implementation, such as the circumstance of lacking visual information mentioned in our previous discussion of the scaling-up problem (Section 2.4.4, page 52).

5.2 The Identification of Tasks.

Existing discussions of active perception adopt certain confusing concepts, each of which must be critically reconsidered before we set off to seek epistemological explanations of activeness.

5.2.1 Analysis of Task Identification

Intentional Description. Two central notions of the active perception perspective – required task and needed information – are intentional concepts. Intention can serve to motivate an agent to accomplish a task, but autonomous agents do not have built-in intentions. They can be configurated to fetch certain types of information or execute certain specific activities (e.g. reflexes), but they are not really driven by intentions. The adoption of those intentional concepts seems to be incompatible with the behaviour-oriented approach, to which the active perception perspectives belong. It is an intriguing epistemological question how a behaviour-based (autonomous) system can realise the existence of certain intentions and proceed to satisfy them.

Tasks, Global Goals and Subgoals. The concepts of tasks, global goals, and subgoals are relative, depending on the respective questions they relate to in the systems of active perception. A task concerns *what* perceptual guidance a particular perceptual system must provide in support of certain bodily actions. Relating to a task, global goals concern the question *what* perceptual guidance the systems of active perception provide in support of a (perceptual) task. By contrast, subgoals concern the question *how* that guidance is generated on grounds of the basic components of such systems.

For example, for a hunter in the jungle a task is to keep track of a moving target, say a moving object hidden behind trees. To keep tracking this target the perceptual systems of the hunter must identify the relevant global goals, such as holding *gaze* on the moving target, relating the gathered visual inputs to the most likely body shapes, and foreseeing the trajectory of the target movement.

Within such general goals, the goal of gaze control can be seen as a task of certain sub-systems, such as vergence, pursuit, and saccade control, of which the mechanism of attentive control can be regarded as a further sub-system.

For a certain global goal, e.g. the attentive control of saccades, there are certain subgoals, such as calculating the relative importance of almost all the features in the present visual scene, and deriving the most important one from among them. As another example, the identification of objects is maintained by a particular tracking mechanism, such as Snake, with the subgoals of identifying component perceptual features (lines, curve, etc.), linking them smoothly with internal continuity, and modifying the smooth contour on the basis of external forces. Note that the subgoals are already implemented in particular mechanisms (e.g. attentive control of saccade) or systems (e.g. the tracking maintained by Snake) of active perception.

Task as Guidance. The task of active perception is perceptual guidance that subserves bodily actions. That is, a designer's envisaged tasks (i.e. the required tasks) are fulfilled when a system of active perception effectively supports the related bodily actions as envisaged by its designer.

For real organisms, tasks of active perception are also cast in the form of guidance in support of bodily actions. However, they are not envisaged by any intentional being. They can be understood in the context of survival, for which a task of a system/organisation is advantageous performance in response to a certain challenge. The performance of active perceptual systems is not bodily action but perceptual guidance in support of bodily actions.

Notice that in the definition of active perception (see Section 1.2.1, page 4) there are no constraints imposed on the nature of its tasks. An active perception system provides perceptual guidance as a direct consequence of its domain – perception, as opposed to motor actions, attention, memory, and language. According to the definition, the guidance provided by active perception could support something other than bodily actions. However, current research in active perception, including the research in neuroscience, such as Churchland *et al.* (1994), has *found* that the fundamental role of active perception is to provide perceptual guidance in support of bodily actions. It is very likely that this is a general consequence of evolution. That is, active perception found on Earth *is* so, while the systems of active perception elsewhere (in other possible worlds) *may* well have as their tasks the supporting of other activities in other domains – attention, memory, language, or even perception itself. However, in the further discussions we respect empirical findings. Hence, the task of active perception remains seen as the production of guidance in support of *bodily actions*.

One may disagree about the interpretation of an empirical fact and argue that the guidance provided by active perception is actually not limited to the support of *bodily* actions. The guidance can support language or thoughts, too. For example, the tasks of perceptual systems may be perceptual experiences in support of language understanding or thinking (e.g. thoughts derived from reading a history book). However, these represent tasks of *perception*, not specifically the tasks of *active perception*. This challenge is consequently met. It remains *true*, on this earth, that active perception, as a particular case of perception, has a narrower range of tasks – providing guidance for bodily actions. Systems of active perception have been *found* as those that provide guidance to support bodily actions.

According to the definition of active perception, it is the *processes* of a perceptual system, not its *produced information* (i.e. guidance), that makes the perceptual system active. The products of a perceptual system (i.e. perceptual guidance) may *subserve* an active system, while the perceptual system *per se* remains non-active. In the above argument about perceptual experiences and language, it may be further contended that the tasks of perception may be the production of guidance to support *active* language interactions and hence active perception can support language – something beyond bodily actions. The reply is straightforward, that the language interaction may well be seen as active but the perception does not consequently qualify as active. One system being active, i.e. driven by active (language) processes, does not make the other system also driven by active (perceptual) processes.

Identification by Run-time Self-programming. If an autonomous agent qualifies as *completely* active, it must be capable of identifying the task from among lots of possible tasks within the niche. Indeed, this must be the case for real organisms, however low level they are, to be able to carry out specific tasks in the real environment. When they come across certain aspects of the niche, they effectively identify the task to perform, and hence they survive. The identification of the task in question is determined by the specific aspects of the niche they encounter together with their autonomous internal control, not by the *deliberation* of an external designer/programmer. The implementation of active perception, as a branch of robotics, may well begin with a programmer's deliberation, but if so it does not explain the biological reality. For behaviour-oriented agents to be really active, the programming itself must be autonomous to a high degree, no matter whether the capability of self-programming results from evolution (as Brooks claims), development, or learning.

It is as yet unclear as to how the aforementioned identification of tasks is accomplished. We can term this problem the *problem of completely active identification of tasks*. In the present thesis we consider this problem and work out sufficient conceptual foundations for its resolution.

We can see this problem as an instance of the scaling-up problem. The organisms (even low level ones) living in their respective ecological niches may encounter a variety of environmental circumstances, which must be identified and certain appropriate motor actuators subsequently be selected to take effect in those circumstances. The scaling-up problem will arise because the ecological niche of organisms is complex compared to the deliberation needed for implementing a single capability in single behaviour-oriented agents.

Desiderata of Needed Information. The derivation of the needed information (which can be seen as the process of pursuing an implicit subgoal) for a required task is important for the implementation of active perception, because in real environments the implemented agents can only collect the needed information sparingly. That is, they arrange their activities to gather information *only* for the need of the required task. How can the *behaviour-oriented* agents know to maintain the economy of the tasks they encounter? The maintenance of that economy during information collection *appears to be* intentional, because these agents effectively and efficiently manage to prevent anything irrelevant to the required tasks. However, as yet it still seems difficult to explain this seemingly intentional behaviour of active systems in the context of autonomous systems. We can term this difficulty the *problem of completely active arrangement of needed information*.

The architectures of autonomous systems, of course, cannot presume the functionality of an internal vital person *who* has sufficient wisdom to manage the needed information. Yet, such wisdom is still needed. If the repertoire of responding activities is pre-fixed explicitly[1], that wisdom can be explained in terms of links between actions, thresholds of action modules, energy spreading and parametric control, as Maes (1990b) suggests. The problem of completely active arrangement of needed information will consequently be resolved. However, this problem seems to be more difficult for systems of active perception, because most of them may shape their responding activities in terms of *implicit* goals (see discussions in Section 2.4.4, page 55). As we will discuss later (see Section 5.4), this is actually the case for most implementations of active perception. For these systems, the aforementioned problem of completely active arrangement, would be difficult to resolve.

In the present thesis we consider this problem and introduce sufficient conceptual foundations for its resolution.

Again, the economy in gathering the needed information, regarding the implementations of active systems, is usually implemented by programmers in virtue of their intentions and wisdom. What is needed and how to respond, in respect of economy, depends on the programmers' strategies of maintenance. Thus, the same problem arises as we discussed previously: if an autonomous system is completely active, it must be capable of selecting and arranging activities from among many possible activities autonomously, effectively and efficiently, in response to the challenges in the niche in which it resides. Hence, to see behaviour-oriented agents as being completely autonomous and active, rather than being entirely reliant on an external programmer, we must explain the notion of needed information in terms of two sources of information, namely their internal control and the specific aspects of the niche encountered by organisms. Also, we can see this problem as an instance of scaling-up problem.

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[1] Examples of itemised economy can be found in a *task-oriented* research, Ikeuchi & Hebert (1991). In addition, within active perception research, Rimey & Brown (1992) is such a case, where a task is achieved by itemised task-specific actions. Such actions are scheduled by Bayesian reasoning.

5.2.2 Two Types of Task Identification

The analysis of tasks would be seriously incomplete if the status of tasks *in* the autonomous systems were not analysed. The latter analysis is important because intuitively it is hard to figure out how it is possible that a task envisaged by a designer with her *intentionality* can be *identified* successfully by an *autonomous* system. The identification of tasks by autonomous systems sounds like a category mistake. However, autonomous systems do perform certain tasks, as demonstrated by the implementations of mobile robotics. It is not simply a scientific fiction, but an experimental result. When we inquire into the machinery in autonomous systems that support their performance, the capability of carrying out tasks should not be attributed to intentionality, because the problem of how to explain the intentionality[2] in autonomous systems is exactly in question (if they can be *interpreted* as having intentionality). We humans can interpret that the mobile robots are capable of maintaining task identification, on the basis of their architectures and performance. As a matter of analysis, task identification can be classified into two types: one on the basis of representations and the other on the basis of performance.

Type One: Tasks Identified in the Form of Representations. Certain tasks are identified in the form of representations, which serve as 'guideposts' (i.e. goals of performance) for the designer to gradually work out perceptual guidance in her designed robots. The task identification is based on representations, in the sense that tasks are realised in behaviour-based systems on the basis of those representations. Specifically, identical representations lead to the same capability of carrying out the same task, and a change in representations leads to a change of task.

The representations may be language-like, distributed, or even basic components of autonomous agents (e.g. Maes (1990b), Steels (1990a)). In order to

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[2] By intentionality here is meant the inner drive of maintaining intentions. Humans, of course including designers, identify and carry out tasks not at random but by their intentions. At this point, intentionality is not meant as the capability of referring to others from symbols/codes.

identify perceptual representations, in the PDP such representations must be associated with nodes; however, representations are not maintained by nodes *per se* but by the patterns of connections *between* nodes. For the autonomous systems with internal representations, those representations significantly manifest (although do not completely characterise) the tasks envisaged by the designer.[3]

Adept is a good example of this. The target is represented in a global map, which shows the target as the final position of Adept's movements among obstacles. The task is to reach that target. While the target is *directly* coded in representations (in the map), the task is not *completely* identified by those codes. It also needs the computation of critical variables concerning the surrounding obstacles and the comparison between the computed values (about the shapes of the obstacles and the distance of the open space between two obstacles) and the target position in the map. It is the mechanisms of computation *and* the representations in Adept together – the target position, shapes of obstacles and the distance of the open space between obstacles – that identifies the task envisaged by the designer. Those representations can be seen as necessary conditions of task identification.

Another example is the attentive control of saccadic movement in humans. A request for visual information may arise from human intentionality, as the task of saccadic movements, and later the pre-attentive mechanism surveys the whole visual scene to determine a single most important feature in relation to that request. Alternatively, no requests are raised in attention, but the pre-attentive mechanism surveys the visual scene to find an request from *memory* for further saccadic movements.[4] The arising request is represented in the attentive control of saccades in the form of weighted visual features (please refer to Robinson (1968, 1987), see Section 3.4.3, page 98), which serve to determine the target position for the next saccade.

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[3] For further understanding, please refer to Section A.2, page 347, and Section 2.4.3, page 49.

[4] According to Mumford (1991), certain hypotheses abut the visual scene are generated in the visual cortex, passed through corticogeniculate pathway to the LGN (a part of the thalamus), stored, filtered/gated and *updated* there (in the LGN). This is evidence showing that the brain (specifically, the visual cortex) raises enquiries about the visual scene, in the form of generating *relevant hypotheses* and *corroborating* the raised hypotheses filtered in the thalamus.

Notice that the aforementioned tasks are not *directly* characterised (by the visual systems) in the category of purpose/intention. In these two examples (Adept and the attentive control of saccades), those tasks are *mediated* by the representations of the target position (in a global map) and *weighted* features (in a selection mechanism). Observers (including the designer), as intentional beings, evaluate the performance of the above two autonomous systems (with regard to their goals of performance) by considering the consequences of these two systems' activities in support of the relating tasks, as the designer intended.

By contrast, the above representations *per se* (as opposed to observers' considerations) do not fall into the category of intention. The architectures of *autonomous* agents need not presume the existence of intention, but such agents remain capable of carrying out tasks. For the above two systems of active perception, the tasks take the form of perceptual guidance, in response to certain enquiries. Thus, the tasks can be seen as being *indirectly* represented in selection mechanisms – the selection over movements toward the target (in Adept) or the selection over weighted features (in attentive control of saccades).

Type Two: Tasks Identified Purely on the Basis of Performance. Other tasks of autonomous agents are not supported by representations, not even in Maes (1990b) where (global and sub-) goals are represented explicitly. While tasks are *envisaged* by their designers, they can only be understood purely on the basis of their *performance*. Observers (of course, including the designers themselves) inquire as to whether certain envisaged tasks are successfully carried out in implementation.

When a task is fully *predicted* by its designer it would not consequently pertain to type one task identification. The behaviour of the wall-following robot in Mataric (1990), for example, might have been fully predicted by its encounter, but no representations are adopted to represent the task. The envisaged tasks of autonomous systems, anyway, must be predicted by the designer, for *both* types of task identification. In contrast, when a robot performs an unpredicted/unexpected task, which is possible although unusual, observers (of course, including the designer who later finds the robot perform previously unpredicted tasks) can identify the tasks purely on the basis of the robot's performance, without knowing anything about the architecture which manifests its designer's attempt (i.e. predicted/expected tasks).

Remarks on Task Identification: Both Types are Essential to Active Perception. Both types of task identification are essential to any active perception system. Although not undertaken in Brooksian robotics, type one task identification is essential to active perception. As previously discussed, a task of active perception must be assigned from the outside. An assigned task is not directed coded in the form of tasks, but is represented indirectly, e.g. by weights in attentive control of saccades and the global map in Adept. By contrast, type two task identification is also essential, because task identification in the autonomous agent approach is intrinsically subject to the examination of performance.

One might contend that the task identification in Brooksian robotics is not *intrinsic* to the design but simply important *practically* (like the design in traditional AI), because a robot may be built by an extremely clever designer without undergoing the process of debug and modification. The task can *in principle* be fully envisaged and implemented if the designer is sufficiently clear. As a reply, there might really exist such a genius, but her success must take account of environmental factors which are seen as complex and somewhat unpredictable. The engineers in traditional AI, by contrast, can ensure success fully through relating theories and guidance written in the manual, with only very rough understanding of the environmental factors (which can even be acquired from books and the manual). For ensuring the expected tasks in autonomous systems, the lesson is that environmental factors cannot be completely manifested without the performance of the particular implemented systems. Hence, we can say that the performance of the implemented system is an intrinsic part of the design.

For the active perception systems in real organisms, the type two task identification remains intrinsic. From a phylogenic point of view, the satisfactory identification of a task is an outcome of gradual modification, which is imposed on the systems' performance. Then task identification consequently falls into the category of type two. From a task-level point of view, a task is carried out stepwise and in each step the *collected* information must be compared with the indirectly represented task. The collected information is an achievement in performance (on the basis of organism-environment interactions), while the comparison (which happens later) is an activity of identifying the task at the next step. In other words, to carry out a task the active perception system must identify it iteratively in each step. In each step, the aforementioned comparison takes place and consequently certain values of the collected information are taken into account. Those values result from the task identification performed at a previous step. Hence, type two task identification really takes a role.

Combining the Two Types of Task Identification. Since both types are essential for each active perception system, task identification must be understood in terms of their combination. In this regard an example may help. The identification of a task for an active perception system is like (though not entirely identical to) a traveller in a historic town, who can only remember street circumstances very locally, making their way toward a monument. Suppose this traveller has a map; she still needs to identify her route regularly in order to approach the monument. This travellers' systems of intention render the task (finding the monument) to all the systems related to navigation, with the task being shaped into certain representations in perceptual systems. In each step of route-seeking the perceptual systems need to re-affirm the task, not only for confirming the previous performance of route-seeking activity but also for *further identifying* the task under different circumstances, that is, in different streets.

This example reveals several forms of task identification in active perception systems, such as attentive control of saccades, pursuit, tracking by Kalman filter, route planning demonstrated by Adept. Any of these examples can be taken as the context of the following analysis.

A task is identified by an organism in four forms. The task is originally identified with an *intention* outside perceptual systems. Later, this intention is *transformed* into certain relating representations (i.e. perceptual features) in perceptual systems. Third, the task is attempted in each step of computation and the result of performance in this step is *evaluated.* Last, the evaluated result is *compared* with the above representations and then the systems again attempt to accomplish the task, by guiding sensory-motor movements so that the further step of computation may approach 'nearer' to the accomplishment of the task, when the task is attempted again. Thus, task identification takes place in each step of computation. In other words, a task needs to be identified iteratively in each step when further processes are arranged. Task identification is not completed once for all, but goes step by step with *process arrangement,* which is a topic of this section.

To summarise, task is identified in four steps: intention which is assigned from outside the perceptual systems, perceptual representations, evaluation of collected information needed for the task, and iterative comparison of the above information with the task for approaching nearer to the accomplishment of the task.

An Epistemological Gap. An epistemological gap needs be bridged: how can an autonomous system ensure something (S) on the basis of its architectures and processes, where S is basically understood from observers' point of view? The question, in a nutshell, is how the autonomous architectures can eventually ensure the externally assigned task (i.e. S) *without directly encoding* it?

Remember from a previous discussion that a task of an autonomous agent (robot) is *externally* assigned by the designer. The above epistemological question thus concerns the derivation of certain global behaviour in response to an enquiry assigned from outside the active perception system.

A Pragmatist Consideration. To answer this series of questions, we should notice the role of the designer. In the design of autonomous systems the designer is the necessary observer. The observer converges on the adequate architectures and processes by assessing the robots' performance. Accordingly, it is reasonable to say that the notion of task identification intrinsically involves a *pragmatist* consideration – that the confirmation of right architectures and processes (about task identification) must (among other things) refer to the robots' performance. Those that successfully lead to the envisaged task are the *right* architectures and processes for that specific task. Thus, task *identification* can be understood as the *initiation* of 'right' processes with 'right' architectures, which are confirmed by performance from the designer's point of view. With such an understanding, discussions of task identification can be focused on the initiation of 'right' processes on the basis of 'right' architectures (right in the above sense).

Given all this, we can further discuss the question of how the identified tasks in an active perception system are eventually accomplished. Consideration of this question goes beyond the category of task identification, which concerns the *initiation* of appropriate processes (as previously mentioned), but instead falls into the category of process arrangement, which concerns the *continuation* of processes leading to the envisaged tasks.

5.3 The Arrangement of Processes

The concept of process arrangement refers to the arrangement of processes in the implemented autonomous system from the initiation of certain processes for an envisaged task, through continual (or continuous) processes with certain serial orders, to the accomplishment of that task.

Good performance of a robot is by no means guaranteed in random architectures. The process of task performance may possibly get stuck at a certain stage. The satisfactory performance of autonomous agents needs to be ensured by deliberately maintained arrangement. How is this accomplished by autonomous systems, given that no homunculus exists to arrange relating processes for the desirable performance? Apparently, consideration of resolutions points to the *design* of autonomous agents.

Satisfactory performance in a full design with a blueprint, such as a clock or a TV, is understood in terms of conceptual connections of cause-effect linkage. However, there is no full design in autonomous systems. The complex and unpredictable environment cannot be fully described in any highly elaborate blueprint, given that autonomous agents must maintain real-time responses.

In the context of active perception, this question can be reshaped: why does the stepwise evaluation of saccadic movements lead to sufficient perceptual understanding? How can the Kalman filter provide satisfactory contours of the moving target? How can Snake keep track of the moving lips (see Section 4.1.1, page 114)? For any system of active perception these questions would arise and demand resolutions.

5.3.1 Analysis of Process Arrangement

Some analyses will make clearer the conception of process arrangement, and hopefully provide more clues as to how such questions can be worked out.

Autonomous System under Design. The process arrangement in autonomous agent research is not maintained on the basis of functional specification. Rather, designers should implement certain modules which carry out the envisaged tasks by organism-environment interactions and/or the interactions between these modules. Designers can deliberate about the architectures of the autonomous systems; however, the satisfactory effects of the aforementioned interactions must be confirmed by the *performance* of implemented systems. The unpredictability of the *real* environment in which autonomous agents are tested can only be manifested by its performance. Like task identification, the performance in the real environment (as opposed to designers' deliberation) is consequently an intrinsic part of design, although it cannot be fully foreseen by designers in their deliberations. Both the designer's expectation and environmental unpredictability should be taken account of in the design of autonomous systems.

Process Arrangement with Exploitative Control. The process arrangement in Brooksian robotics is behaviour-based, if the notion of process arrangement makes sense there. By contrast, the process arrangement with recourse to *internal* processes and representations needs exploitative control, i.e. control over such internal processes and representations. It is not hard to understand that the control is different between exploration and exploitation while between them there may be cooperation.

Three Requirements of Process Arrangement. Process arrangement may be not easy to understand in terms of *sufficient conditions.* Below we discuss certain important *requirements* of process arrangement.

Process Arrangement as Emergence. Given the indispensable involvement of the designer's (debugging and) modification (based on *performance*), the machinery of the implemented *autonomous* system, and the aforementioned interactions under environmental unpredictability, the arrangement of processes seems not a matter of fully local functional control. Instead, the process arrangement is very likely to be a matter of emergence, i.e. global behaviour on the basis of local activities. If the architectures of the implemented autonomous system consist of different types of emergence (as argued in Clark (1996)), e.g. that of Brooksian simple automata, or that of the internal representations adopted in Maes (1990b) (also in Steels (1990a)), understanding the above emergence would need consideration of the *interlock* across different accounts of emergence (recall the notion of inter-paradigms interlock in Clark (1996)).

Process Arrangement as Autonomous Planning. The process arrangement supported by autonomous machinery can largely be understood in terms of autonomous planning discussed previously (in Section 2.4.4, page 53), although the nature of the components in systems of active perception and that in Maes (1990b) may be different.[5]

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[5] As will be seen in later discussions, the components in systems of active perception are *quasi*-functional modules and *quasi*-action modules, which are different from the components in

Iterative Process Arrangement that Shifts Processes between Goals. The process arrangement for a certain task may shift back to the stage of task identification and subsequently opt for another task. Remember that the concepts of task and goal are relative (see Section 5.2.1, page 146). If we interpret such tasks as goals in relation to a hidden task at a global level, the above statement can be seen from a different angle: an autonomous system may carry out a task by shifting between goals.

Shifting between goals is a phenomenon particularly seen in Maes (1990b) in the notion of autonomous planning under the circumstances of high ϕ and low γ, high sensitivity to current internal states and low sensitivity to the previously assigned goals (see Section 2.4.4, page 53). As previously discussed, organisms may accordingly be highly opportunistic (as opposed to goal-oriented) and adaptive to current situations (i.e. not sticking to on-going plans[6]). Because the basic components of active perception may be different from those in Maes (1990b) (i.e. competence/action modules), the autonomous planning between them may consequently be subject to different types of control. As seen in chapters three and four, energy spreading seems to be adopted (in Snake) but apart from this there are a variety of control – such as attentive control of saccades, dynamical systems (in Dickmanns' car and the dynamic Kalman filter), and any other exploitative control.

Given the above discussions about the nature of process arrangement, the following discussions provide more detailed understandings of its machinery.

5.3.2 The Machinery of Process Arrangement

Operation-specialist Systems of Active Perception. The machinery of process arrangement can be extremely complicated if its processes are maintained

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Maes (1990b) (competence/action modules).

[6] Although the relation implemented in Maes (1990b) can maintain autonomous planning, the task is pre-fixed, without considering the complexity of autonomous task identification. The implementation simplifies task identification (by pre-fixation) in exchange for a focus on process arrangement (by autonomous planning).

by a long chain of mechanisms and certain of those mechanisms are huge. For a single sub-system of active perception, such as the pursuit system[7], nature seems to opt for a *small* repertoire of capabilities which consists of *simple* modules, as seen in the six sub-systems of gaze control. Each sub-system addresses a specific control, e.g. the control of pursuit movements.

This seems to be also the case in design. For example, Adept is itself an operation-specialist system – for exploring free-space – and it comprises a small repertoire of simple modules, such as modules that serve to compute various critical variables (see Section 4.2.1, page 126). The modules in this repertoire are numbered about five, each of which only serves to compute the value of a certain critical variable, such as curvature or distance.

For convenience of discussion, certain terms used in the present thesis are somewhat subject to convention. According to everyday language, simple modules can be seen as small modules, and a small repertoire of capabilities is itself simple to a certain extent (i.e. not complicated). However, later discussions will term them *small* repertoire and *simple* modules, although 'small' and 'simple' (in the context of describing modules) seem interchangeable. In addition, a system will be said to have a repertoire of *capabilities*, while a capability in this context only consists of a simple module, the mechanism of overshoot maintained by the control of pursuit movements.

The following discussions focus on the nature of single systems, such as

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[7] The distinction between a system and a sub-system is relative, as evidenced by the literature of active perception. A system of active perception, such as a pursuit system, rigorously speaking, is a perceptual *sub-system*, when it is compared with a global perceptual system, such as the active perception of humans. However, it can be independently called a pursuit *system*, for the sake of convenience. Furthermore, even the distinction between systems and sub-systems is not complete. There are yet other systems standing between them, such as the system of gaze control, which itself consists of a number of sub-systems – i.e. focus, vergence, appropriate aperture, pursuit, the attentive control of saccades, and the gaze movement for tracking (as opposed to the grasp of deformable contour – e.g. Snake) (see Section 3.4, page 95). Still, a tracking system can indeed be divided into several sub-systems, such as a Kalman filter which tracks a deformable contour and dynamical systems which keep track of moving targets. Further, the perceptual system in Dickmanns' car stands in the middle range between a tracking system and a whole perceptual system of an organism, for it consists of many tracking systems, but ends up with a simple perceptual system, compared to the perceptual systems of *real* organisms. According to above analyses, the framework of perceptual systems does seem to be divided neatly into three scales – system, sub-systems, and modules. Hence, discussions must be careful about such relative divisions, in order to avoid confusion.

Adept, the dynamical Kalman filter (as a single tracking system), and saccadic control. The emphasis is on the relationship between their architectures and functionality. Each such system can be regarded/defined as an *operation-specialist system* of active perception, given that it serves to maintain a specific type of operation for[8] achieving perceptual functionality, such as pursuit or saccadic control. In addition, subsequent discussions address the relationship between such single systems and the further global systems they play a role in, such as gaze control and Dickmanns' car. Each of such semi-global systems maintains a somewhat complicated combination of perceptual functions. The aim of the following discussions about such operation-specialist systems is to argue for a *small* repertoire of capabilities on the basis of the *relationship* between their functionality and architectures.

The Matter of Inter-connections in Brooksian Robotics. In the context of autonomous agents in general, including the systems of active perception, the size of the repertoire seems to matter for the *maintenance* of specialist operations and the related functionality. By analogy with the small systems in active perception, Mataric's wall-following robot (Mataric 1990) can be regarded as an operation-specialist system. The repertoire of its capabilities is very small, containing only three automata *Stroll*, *Avoid* and *Align*, so that it is good at wall-following but cannot respond to visual contours at all.

The size of this system seems to manifest certain constraints for the maintenance of its functionality. Between these three automata, according to its architecture, there are strict interactions specified within the instructions for single automata. Remember the architecture (see Section 2.4.2, page 46):

- *Stroll. When there is no obstacle in front,* move forward in a more or less

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[8] Three caveats must be entered with this definition. First, such operation-specialist systems are not a particular case of specialist systems in traditional AI. Secondly, like the aforementioned concept of sub-system, the concept of specific type is *relative*. It is relative to the degree of specificity. Because of different degrees of specificity, either the *attentive* control of saccades (as opposed to the reflexive mechanism of saccades) or *gaze* control (as opposed to the grasp/understanding of target contour) can be seen as control of a *specific* type, depending on the range of specificity concerning the type in question. Thirdly, the term 'for' means contributing-to, which has no teleological implication.

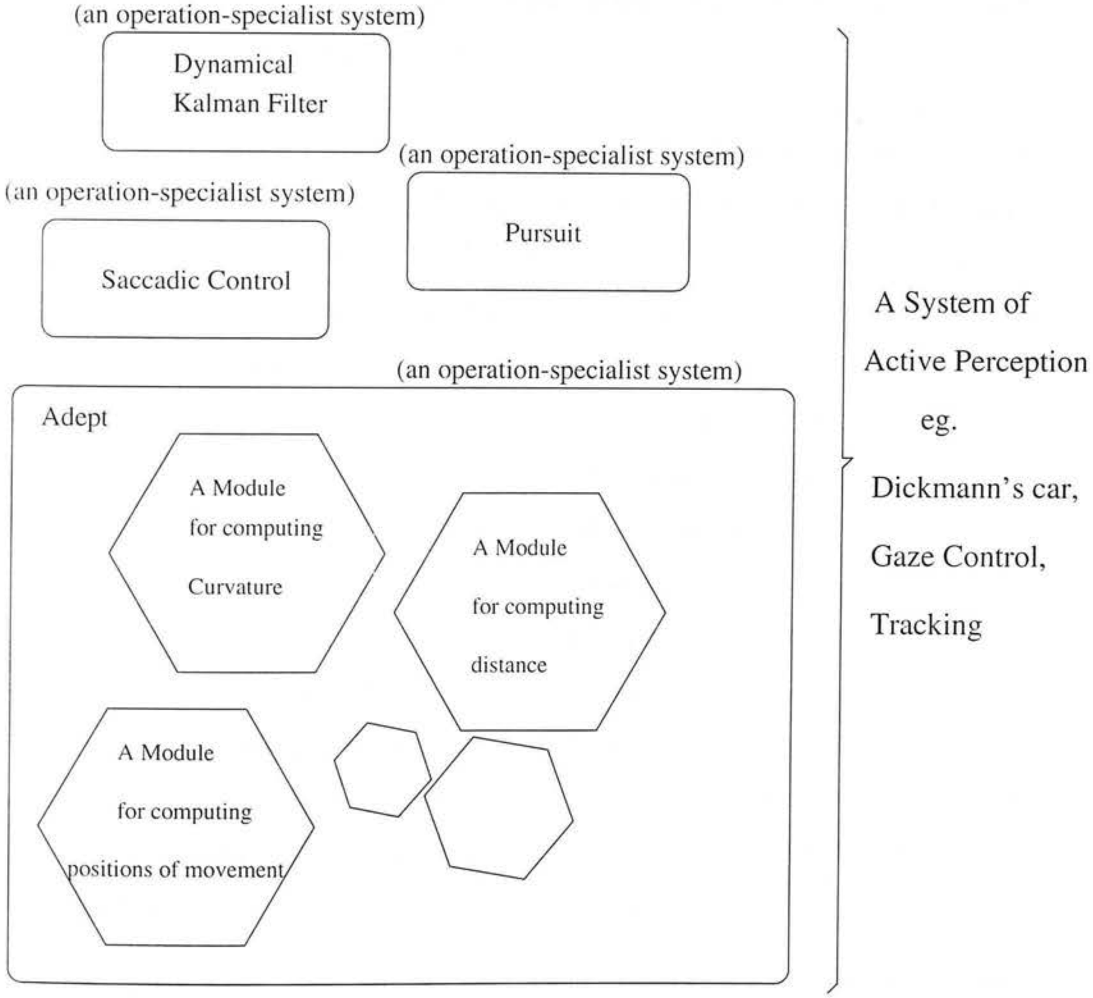

Figure 5.1: **A Brief Sketch of the Relationship Between Simple Modules and Sub-systems.** A sub-system of active perception, such as Adept, saccadic control, or the dynamical Kalman filter, consists of a repertoire of capabilities, each of which further comprises a variety of simple modules for computing specific perceptual features. Each of such sub-systems can be seen as an *operation-specialist* system of active perception.

straight motion. *When the robot encounters an obstacle*, stop, and follow the instruction of **avoid**.

- *Avoid. When there is an obstacle in front*, turn right or left.
- *Align. When the distance to the object behind is shorter than the distance in front*, turn by a small angle.

The combination of its simple modules, i.e. the three automata, is by no means trivial. Between such simple modules there are inter-connections for mutual coherence. Firstly, they are well connected. The initiation of the automaton *Avoid* is stated in the instruction of another automaton *Stroll*, which concerns the existence of an object in front – which is taken as an obstacle. The initiation of yet another automaton *Align* depends on the comparison of distance between an object behind and one in front. Secondly, the conditions of initiation for each of these three automata must be well connected, in the sense that they are mutually exclusive (so that a decision can be singled out), complete (so that the robot will not entirely sit idle and fall out of control), and linked smoothly (so that the robot's 'decision flow' can respond to various environmental conditions without being trapped in a single state). Thus, the incorporation of an additional automaton would not be a matter of trivial combination, because it will affect the previously established mutual connections by conditioning the additional automaton in the previously established inter-connections.

The inter-connections of Brooks' three-layered robot is also not trivial, for the layer control is not so simple as the single automata. This is not hard to see if we examine the architecture of the third (top) layer (see Section 2.3, page 32). This layer serves to produce a pathplan. This is controlled by an automaton *integrate*, which maintains a rigorous priority control (see page 36) to integrate the initiation of automata within these three layers. The priority control, on account of the conditions of suppression and modification between automata, is by no means as simple as the automata in previous two layers, in view of its conditions of initiation.

The incorporation of further layers is very likely to generate further degrees of complexity in between-layer connections/control. However, gradually evolving more-layered robots on the basis of previously achieved layers remains less complex than a blend of modules without layer control. Although evolving layers to previous robots is a challenge to Brooksian robotics, the attempt at building a robot beginning with a large repertoire would be unnecessarily complicated and difficult. Such a robot would be tantamount to an attempt without sufficient layer control. Brooks' conception of layer control, as a *requirement* of the subsumption architecture, indeed manifests the importance of keeping the architecture of *an* operation-specialist system (as manifested in a single layer) small. The inter-connections under such control would make the implementation of the robot's functionality less complex.

The Ease of Engineering and Intrinsic System Complexity. The requirement of subsumption architecture, i.e. the *gradual* implementation of layers, stands both as a concern for the ease of engineering and a consideration of system complexity. This requirement may not only be unique to Brooksian robotics but may be extended to other de-centred approaches to computation. Here the subsumption architecture serves as the initiation of discussions.

Regarding the ease of engineering, the layered-control is necessary for the maintenance of robot implementation, in order to circumvent unnecessary complication in implementation. Simple systems would be *easier* to maintain than complicated ones. This is a requirement grounded on *practical* consideration.

By contrast, the consideration of system complexity leads to a stronger requirement, which is instead a *theoretical* reason. That is, a system may have an intrinsic limitation in its complexity. Two examples serve to make this point clear. First, while linear systems manifest a variety of linear properties, the complexity of non-linear systems would increase exponentially with the size of that system. Although nature is possibly to have an exponential degree of complexity (the impossibility itself may be hard to prove), the generation and maintenance of a system manifesting such complexity would less likely to succeed.

Second, neural networks with larger architectures would take a much longer time than the required to generate a novel capability (e.g. understanding a novel language feature), because the complexity involving in the compartmentalisation of state space would consequently rise. The limitation in this case will be discussed later.

The theoretical reason for incorporating limited components and state space in a de-centred system may need more studies before it is fully justified, or modifified. If nothing goes awry within a system (a design or natural system), it is basically hard to prove (or even hard to conceive) that the complexity of the system has risen up to a level that a system itself risks collapsing. However, the above two points indicate the likelihood of complexity limitation intrinsic to de-centred systems.

The Size of an Operation-specialist System of Active Perception. The implementations of active perception normally consist of one or only a few operation-specialist systems, each of which has a limited repertoire. For example, saccadic control consists of two operation-specialist systems. One is the attentive control of saccades, while the other serves to transform the produced guidance into the motor commands for head and sensory-motor movements (Clark and Ferrier 1992). In addition, as surveyed in chapters three and four, the number of modules is also limited in other operation-specialist systems – Adept (for moving away from obstacles toward target), the dynamical Kalman filter (for keeping track of the target and grasping its contour), the pursuit system (for the pursuit of moving target), etc.

The reason for keeping the size of an operation-specialist system small, without grouping larger sized features together in the same system, is very likely to be similar to that given in the previous discussion regarding Brooksian robotics – i.e. for making simpler the inter-connections of its architecture (of the operation-specialist system in question), which in turn facilitates the robot's functionality. An example suffices to make this point clear – Dickmanns' car, for which the task is to drive adaptively in the motorway.

The perceptual inputs are gated by certain *parallel* small-size modules which present different operation-specialist mechanisms of process selection, such as lane keeping on road, speed adjustment to road curvature, driving at night, detecting obstacles, stopping in front of an obstacle, convoying (driving behind another vehicle), stop-and-go behind a preceding vehicle, and the lane changes triggered by a human operator in order to avoid other vehicles in the neighbouring lanes (Dickmanns 1992; see discussion in Section 4.2.2, page 132). Each module maintains a specific mechanism of process selection, which provides certain specific performances once certain relevant sensory inputs (to that mechanism) are dealt with and certain intra-mechanism processes are subsequently initiated. Otherwise, it would be difficult for an autonomous car to maintain a variety of tracking tasks (as shown above) without the design of such parallel modules. Consider the circumstance where all operation-specialist systems in Dickmanns' car are conflated into a single system. Then, a difficulty would arise immediately, that all the control parameters of each previous operation-specialist systems join together in a single system. This would be a difficulty for the implementation of dynamical systems: finding out the regularities of control parameters in a single system is practically difficult, and hence it would much more difficult to extract regularities from a blended system than from the simple tracking systems, for reasons as follows.

The practical difficulty for finding out the regularities of a dynamical systems cannot be overlooked, because it is a bottleneck for dynamical systems modelling. This difficulty is reported by Thelen and Smith (1994), as a general difficulty for dynamical systems modelling. The difficulty is also confirmed by Grossberg (1995) in the establishment of differential equations for his model. This difficulty is even seen, by Eliasmith (1996), as the main difficulty of the dynamical systems approach to cognition.

A good strategy of avoiding such a difficulty is to organise a dynamical system with recourse to parallel or heterarchical structures, as demonstrated in the implementation of Dickmanns' car. Without such parallel or heterarchical structures, the implementation of dynamical systems would be less feasible.

Keeping the Architecture of a Module Small. In general, the architectures of a module should be small for behaviour-based systems, as previously mentioned (see Section 1.2.2, page 9). The accomplishment of tasks in behaviour-based systems is determined by both built-in task-specific facilities/utilities and on-line computation. As regards on-line computation, the current states and goals are maintained by a variety of modules, depending on the tasks and the environment. It is worth noting that the control of a behaviour-based system is distributed, which may result in high *complexity*, as Mataric (1993) indicates, unless the inter-module dependence and computation is minimised.

A General Consideration of Size in Developmental Psychology. Consideration of small-size systems seems to have its roots in developmental psychology. As reported by Elman (1993) and Elman *et al.* (1996) on the basis of certain connectionist simulations, development of neural networks *must* 'begin with small' (architectures).[9] Development of neural networks must follow a process of gradual expansion of the previously developed networks. Otherwise, the learning beginning from large may end up not learning the required task.

Specifically, Elman *et al.* (1996) explain the importance of two modes of incrementation – incremental learning and incremental adding of architectures. Because the considerations of small-size systems concerns the size of the repertoire of capabilities, not the size of architectures, our argument only relates to the former mode of incrementation – incremental learning. Elman argues for the importance of incremental learning, i.e. learning the (specifically, language grammar) features of increasingly degrees of complexity, with the argument being grounded on the complexity involving in the compartmentalisation of state space. Briefly, the compartmentalisation of state space (which is not identical with the compartmentalisation of hidden layers) is successful only when the learning features are very limited, even if there are sufficiently large[10] architectures available.

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[9] The phrase 'begin with small' appears as a slogan of Elman *et al.* (1996). Specifically, they argue for small *architectures*.

[10] Too limited architectures might be not enough for learning complex features, as is easy to realise intuitively: Sentences with increasingly more complex features need increasingly more architectural resources.

This does not mean that neural networks cannot learn complex features at all, but means that such features cannot be leant simultaneously. A sentence with complex features, say 'girls who chases dogs hits [a] cat', can actually be learnt, but it *only* happens *after* the neural networks have already learnt some of their related simpler features, such as 'girls chase dogs'. Adding to the previously learnt capabilities, the neural networks in question only need to *deal with a small number of features at each step of learning*, such as the additional 'who' clues, which is certainly small in size compared to the whole sentence. The complexity of learning features is consequently reduced, hence the compartmentalisation of state space is more likely to be successful.

The previous argument about incremental learning underpins the point that learning of cognitive features in connectionist computation must be grounded on a small repertoire of capacities, for easy compartmentalisation of state space at each step of learning. The lesson for our argument about a small repertoire of capabilities, is that within a single operation-specialist system there must be incremental structures of compartmentalisation in 'place', in order to reduce the complexity of computation in a de-centred approach. Thus, it seems very likely that the implementation of capabilities in a single operation-specialist system, although it conforms to another de-centred approach to computation, must maintain the incremental structures of compartmentalisation for the computation. The hierarchical structure implemented in Dickmanns' car is an example, in which the compartment of the 'state space' (for computation) is not realised in the incremental steps of learning, but in the hierarchical structures between component tracking modules/sub-systems. Despite the difference in their respective de-centred approaches to computation (between PDP and autonomous agents), the notion of 'incremental compartmentalisation of state space for reducing computational complexity' seems to be also applicable to active perception systems, provided that the conception of *incremental compartmentalisation* is not simply understood in the dimension of time but in the dimension of design connections. Apart from the hierarchical structures of Dickmanns' car, another example is Brooks' three-layered subsumption architecture.

Process Arrangement in an Operation-specialist System on the Basis of Small State Space. If we see a neural network as a system with specific functionality, then it can be regarded as an operation-specialist system. The report by Elman *et al.* (1996) can be seen as a support for the previously discussed requirement for small repertoires in operation-specialist systems. The compartmentalisation of state space for an operation-specialist system should be small for the generation of a novel capability. A system with a large number of capacities must develop gradually, by development within a small compartment of state space and then slightly expanding the architectures[11] for the further implementation/development of capabilities.

Keeping the state space small can be understood as keeping the within-system inter-connections reasonably simple. The generation of novel capacities/capabilities in a operation-specialist system, as a consequence, has a basis in the maintenance of limited inter-connections within the system.

Growth into a System with a Larger Repertoire of Capabilities. The argument for small networks made by Elman *et al.* (1996) indicates not only the need for small within-system inter-connections in maintaining single operation-specialist systems, but also the conditions of network/system growth for generating novel capabilities/capacities. Like the expansion of neural networks previously mentioned, the development of more capabilities by a system must be grounded on previously established small operation-specialist systems, and the growth of a novel capability takes only a *limited* amount of *additional* architectural compo-

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[11] Expanding the architectures would naturally lead to the expansion of state space. However, what directly matters for the generation of a novel capability is not the architectures *per se*, but their consequence for the compartmentalisation of state space. If sufficient compartmentalisation of state space can be provided without changing the architectures, the generation of novel capabilities would be equally successful. This is point is exemplified by Joyce (1996), where the expansion of state space for compartmentalisation is carried out by implementation of certain specific noise which fails action potentials of axons but leads to higher degree of distribution between connections of the neural networks. The effect for computation is that the state space for compartmentalisation extends, and the learning of novel complex features is still demonstrated, which was previously exemplified in Elman (1993) and Elman *et al.* (1996) by gradually expanding architectures. The architectures *per se* in Joyce's experiment are left unchanged, yet the generation of novel capabilities is shown to be equally successful. As a lesson from Joyce's experiment, the extension of state space for compartment is more primarily more important than the expansion of architectures.

nents (such as the nodes and connections in a neural network). This is to ensure limited inter-connections among components of a single system.

A Concluding Remark on Limiting the Size of Operation-specialist Systems. The limitation of size for the implementation of operation-specialist systems were previously supported with three examples: the control of behaviour-based systems (simple automata, as Mataric (1993) indicates), the subsumption architectures of Brooks' three-layered robots, and the architectures of neural networks in developmental psychology (starting small, as Elman (1993) and Elman *et al.* (1996) contend).

The limitations imposed on such architectures can be underpinned by practical and theoretical reasons. From the practical point of view, keeping the size of a repertoire small facilitates the ease of engineering. This point is evident in the implementation of the above-mentioned systems. From the theoretical point of view, the small-sized architectures have been insisted on for the feasible control of two kinds of systems: behaviour-based systems and connectionist modelling of cognitive development.

Without understanding the above considerations of size, it would be difficult to explain systems with *large* repertoires. If operation-specialist systems must be permanently small, two questions would naturally arise: one, how is it possible that nature evolves large repertoires for higher organisms? Two, how is it possible to implement a system of active perception which has a large repertoire of capabilities?

The first question is reserved for chapter six, where the role of the environment in shaping systems of active perception will be addressed. Here discussions focus on the second question. Systems of active perception certainly can have large repertoires, as demonstrated by Dickmanns' car (which is a blend of *tracking* sub-systems) and the system of *gaze* control in humans, which are both operation-specialist systems – i.e. systems with a specific set of operations for achieving perceptual functionality. The question, in a nutshell, rests on the maintenance of inter-connections in a operation-specialist system. As a matter of analysis, the maintenance of such large repertoire of modules in an operation-specialist system can generally take shape in two ways, among others:

1. Maintenance Through Certain Links Between Different Operation-specialist Systems. Given that the concept of operation-specialist system is relative, depending on the range of specificity concerning the type in question, an operation-specialist system with many component modules can be divided into many systems which still qualify as operation-specialist systems. If the large repertoire of capabilities are first grouped separately into different operation-specialist systems, then the question, in turn, becomes a matter of links between operation-specialist systems. An example is Dickmanns' car, as previously mentioned. Between various tracking systems (each of which is a dynamical model/system) a link is maintained by generic control procedures (see Section 4.2.2, page 132).

2. Maintenance Through Within-system Relational Structures. It is conceivable that a variety of elements within a system can be ordered by certain within-system *relational structures*, as opposed to *random* ordering of those elements. Such relational structures are found in the ordering of perceptual objects (as opposed to number or language terms) maintained by primates, as reported by McGonigle and Chalmers (in press). A variety of shapes (up to nine) with random colours and orders are presented to monkeys, who are trained to identify those shapes in a certain serial order. Eventually these monkeys learn the task (while pigeons do not). With certain related experiments the above authors find that the monkeys in question do not maintain the envisaged seriation directly by a linear serial order, but maintain it indirectly by a *hierarchical* structure, under which the small number of each pattern makes easier the seriation of the object in that pattern. Further on, between the previous patterns a higher-order relational structure is maintained, etc., which leads to the complete seriation of all objects.

The establishment of relational structures is based on *patterns* of component objects. Each pattern consists of a limited number of component objects.

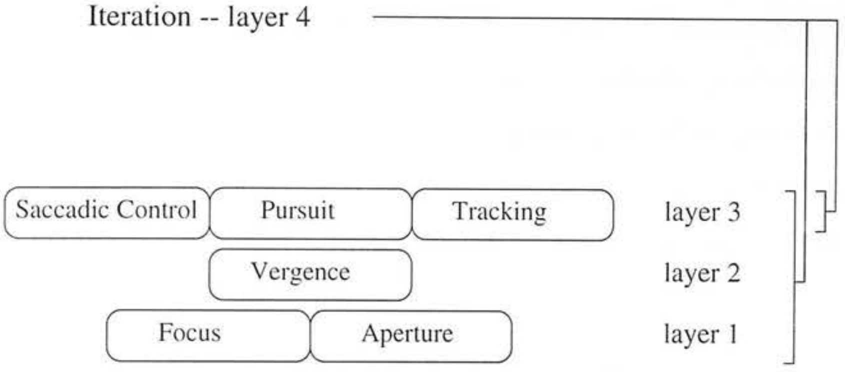

Figure 5.2: **The Hierarchical Structure of Gaze Control.** A hierarchical structure is seen with four vertical layers.

Can the organisation of a large repertoire of capabilities for active perception also be supported by certain patterns and similar relational structures between them? Certain implementations confirm this – Dickmanns' car and gaze control. Regarding Dickmanns' car, the generic control procedures for ordering different tracking systems can be seen as being supported by relational structures, otherwise there is no control at all. Regarding gaze control, there are relational structures between its six component sub-systems (see Section 3.4, page 95): firstly there are both focus and appropriate aperture, then vergence between two foveae, later the attentive control of saccades, still later pursuit, and lastly tracking (optional, only for larger scale movements than pursuit); further on, iterative cycles of the latter three[12] processes push forward the complete route of gaze. A hierarchical structure is seen with four vertical layers: focus and appropriate aperture together, vergence, the other three components, and the iteration of the third layer (attentive control of saccades, pursuit, and tracking) or (when gaze undergoes a sudden jump) the iteration of all these three layers. Notice that each component is itself an independent[13] operation-specialist system while between such systems there are no further operation-specialist systems. Thus, a hierarchical structure is found in the processes of gaze control.

According to the above analysis, the above two categories (inter-system links

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[12] If a distant strong stimulus suddenly appears in visual scene, gaze would be attracted toward it, meanwhile a new cycle of *six* processes may begin, from focus or/and appropriate aperture.

[13] Although the computational results of the three third-layer systems manifest a serial order, such systems maintain their respective operations independently (somewhat in parallel).

and intra-system relational structures) can be combined, as manifested in the processes of gaze control, where each component is itself an operation-specialist system. A tougher question arises about the system of active perception as a whole (such as *the* system of active perception in humans): can the process arrangement of active perception be explained in terms of either category, or the *combination* of these two categories?

This question will be considered in later discussions in this thesis.

A Concluding Remark about the Machinery of Process Arrangement. The above discussions indicate that the machinery of process arrangement for an operation-specialist system must be based on small architectures. An operation-specialist system with a large repertoire should expand from small operation-specialist systems, on the basis of two categories – inter-system links or intra-system relational structures. This is a requirement for understanding process arrangement, but not a sufficient condition. Subsequent discussions should address additional questions as to how the task emergence of active perception on the basis of small architectures can be explained more fully.

5.3.3 Summary of 5.1, 5.2, and 5.3

To summarise, the above three sections consider a fundamental question of this thesis – how active perception systems (as behaviour-based systems) can respond to environmental challenges – with regard to the task identification and process arrangement of active perception systems.

Regarding task identification, the task of active perception is to provide perceptual guidance of bodily actions. It is contended that the tasks of active perception arise either externally from intention systems, or internally from exploitative cues, which are shaped as built-in heuristics. For either of them, the successful identification of a task in an active perception system requires both the implementation of certain *representations* and the modification of the system's architectures through its *performance*.

Regarding process arrangement, discussion (page 174) indicates two requirements about the machinery of process arrangement. First, the machinery of process arrangement for an operation-specialist system must be based on *small* architectures. Second, an operation-specialist system with a large repertoire should expand from small operation-specialist systems, on the basis of two categories – intra-system relational structures and/or inter-system links.

5.4 Quasi-functional Modules and Quasi-action Modules

A fundamental difference between the implementation of autonomous agents and that of active perception, as manifested in the implementations discussed in chapters three and four, lies in their respective basic components. The implementation of autonomous agents, as demonstrated in Brooks (1986, 1991a), Steels (1990a) and Maes (1990b), presumes explicit action modules, each of which specifies a particular spatial action or motion. Such action modules carry out certain activities in contact with the environment, with the effect of detecting or changing environmental conditions, or giving or receiving influences from other action modules.

Active perception is implemented in autonomous systems. However, they are not autonomous *agents*, because such systems do not consist of *action* modules. The basic components of those systems, as seen in chapters three and four, are sensory-motor movements, and the computation that serves to derive certain *critical variables* for the control of sensory-motor or bodily movements.

Sensory-motor Activities. The sensory-motor movements differ from the spatial movements carried out action modules by only detecting environmental conditions without changing them, and by only receiving influences from other action modules without influencing them. The sensory-motor activities, like action modules, can be characterised explicitly. However, the spatial control of sensory-motor activities is vastly more subtle than that of action modules.

5.4.1 Basic Components of Active Perception Systems

Computation of Critical Variables. The control of sensory-motor activities is managed by the computation of *critical variables*, such as the derivation of $\mathbf{T}$, r, N, κ_n, τ_g in Adept for deriving certain geographical paths (see Section 4.2.1, page 126). Furthermore, tracking also needs the subtle computation of various critical variables concerning object shapes (see Section 4.1.3, page 122). By contrast, the control of action modules basically takes the form of simple automata which directly manage organism-environment interactions without recourse to the computation of such variables. Even if those simple automata are further subject to internal control, such as the parametric control (e.g. γ and ϕ) indicated in Maes (1990b), no computation of critical variables is required.

Implicit Goals Realised by Quasi-functional Modules and Quasi-action Modules. We contended previously, in chapter two (see Section 2.4.4, page 55), that both the global goals and subgoals of the systems of active perception are implicit. We describe the implicit subgoals with the term '*factorial conditions*' (of sensory-motor or hand actions), which denotes the perceptual factors gathered through sensors and transformed via numerical computation, such as the visual contours dealt with under visual filters (e.g. the Kalman filter – see page 119) and the features fetched in the attentive mechanism of saccades (see Section 3.4.3, page 98). Such conditions are not functional descriptions (see previous discussions in Section 2.4.4, page 57), but are numerical transformations (through various perceptual mechanisms) of the perceptual features emanating from the external world.

The factorial conditions within active perception implementations, despite not being functional conditions, still have a bearing on the resulting functional control, as is evident by their contribution to the designer's envisaged tasks. Such factorial conditions do not in themselves describe the external world (see the descriptions in Maes (1990b)), nor do they constrain actions directly (see again the above descriptions and the geographical agents in Steels (1990a)). However, they may be seen as productions of *quasi-functional modules*, in the sense that such factorial conditions contribute *indirectly* to *functional descriptions* (see our previous discussions in Section 2.4.4, page 57).

Providing Functional Descriptions. The sensory inputs of active vision systems are gradually transformed into functional (visual) features, as evident in a variety of active perception implementation. The attentive control of saccades serves to gather interesting visual features, which take shape in the form of functional descriptions. Regarding tracking systems, Snake presents various images (see Section 4.1.1, page 114), while the dynamical Kalman filter provides judgement about visual inputs and presents them in form of various visual features. In addition, the computation of critical variables maintained by Adept (see Section 4.2.1, page 126) gives rise to visual features. For example, the curve normal N indicates the degree of curvature of the envisaged surface at a certain point. The normal curvature κ_n refers to the curvature of a certain curve-section.

The visual features indicated in the above examples show that active vision systems partially *recover* the external world, by providing visual descriptions (recall Section 2.7, page 73, and see Section 7.5.2, page 311).

The Subordinate Status of Functional Descriptions. Note that the aforementioned visual features are *partial* functional descriptions. For an active perception system, the modules subserving the recovery of functional descriptions do not provide *full* descriptions of the external world. Rather, only the perceptual features that relate to required tasks are derived and presented in the perceptual scene. Such modules do not purely serve to provide functional description, but are primarily constrained by their consequences for certain bodily actions, depending on the emphasises of the required tasks. In short, only the perceptual features which are relevant to the required tasks can be processed. For such modules, the production of functional descriptions seems to be *subordinate* to the bodily actions which relate to the required tasks. Functional descriptions are not provided simply because perceptual systems serve to provide perceptual features. Rather, they are produced insofar as they are *needed* for guiding certain bodily actions. Given their subordinate status, such modules are termed *quasi-functional modules.*

Quasi-action Modules. Some other factorial conditions may be regarded as productions provided by *quasi-action modules*, in the sense that such conditions contribute indirectly to motor actions. Specifically, those factorial conditions constitute action *control* of sensory-motor movements, without directly driving motor actions. In other words, quasi-action modules provide *perceptual guidance* for bodily actions, but such guidance is neither bodily actions themselves nor the control pertaining to motor systems.

For example, the computation of critical variables (as in Adept) leads to certain guidance of sensory-motor movements, but such guidance is insufficient to specify sensory-*motor* actions, unlike the specification of actions in Brooksian robotics (e.g. automata such as *avoid* in Brooks' three-layered robot), in Steels' exploitation (e.g. the 'agents' with geographical representations in Steels (1990a)), or in Maes (1990b) (e.g. the action module *PICK-UP-SANDER*, which produces a motor action). Without guidance sensory-motor activities are blind, but without actuator mechanisms guidance cannot lead to actions.

The attentive control of saccades, for example, provides guidance that directs the fovea to certain important features in the visual scene. However, the guidance is not tantamount to the mechanism of a (sensory-)motor action. The saccades are driven by features but not by their locations (see Section 3.4.3, page 98). To actually move toward the locations with those features, the sensory-motor systems need to be further controlled by motor systems which serve to identify certain locations for sensory-motor movements and derive the motor actions toward those locations.

As a further example, the mechanism of visual pursuit brings about certain confinement and modification of saccadic movements, by controlling the saccadic direction and range of a saccadic 'overshoot' (see Section 3.4.5, page 107). Nevertheless, the computation of the direction and range of overshoot does not in itself constitute an action module. The computational result serves to provide *guidance for* the saccadic movements of the fovea, by *modifying* those movements. Without the saccadic movements, that guidance *per se* cannot move.

One might contend that the guidance provided by quasi-action modules shows that such modules (despite not being action modules) are indeed *functional* modules because guidance consists of functions. This argument is grounded on a confusion, namely that guidance consists of information and accordingly is necessarily subject to functional specification. This is very unlikely. The guidance does not aim to provide perceptual functions, but concerns the direction and range of the *movements* in question (i.e. saccades). The movements are apparently not tantamount to the perceptual functions. The guidance, as a consequence, is supported neither by an action module nor by a functional module.

The motor actions controlled by factorial conditions are not limited to sensory-motor movements. It is worth noting that the computation of critical variables in Adept not only guides Adept's sensory-motor movements but also its bodily movements. By the computation of critical variables, Adept (as a robot) not only directs its sensors to relevant target areas but also moves itself. The bodily movements are eventually guided to a pre-fixed target position – its destination.

Examples of Systems which Include *Both* Quasi-functional Modules *and* Quasi-action Modules Simultaneously. Quasi-functional modules *and* quasi-action modules are not mutually exclusive. A single mechanism can provide both of them simultaneously.

The mechanisms of computing critical variables in Adept fall into this category. Such mechanisms are quasi-functional modules because the functional descriptions to be generated are subordinate to the requirements of the task, and because they still lead to *representations* of location which are compared in the pre-fixed map with the location of the target. They are quasi-action modules because they provide guidance for Adept to move.

In addition, the dynamical Kalman filter comprises *both* quasi-functional modules and quasi-action modules. The transformations of perceptual features are produced by quasi-functional modules. By contrast, the incorporated *a priori* knowledge serves as guidance for the evolving target in the next moment, regarding its most likely positions in motion and its most probably shapes.

5.4.2 A Comparison between Quasi-action Modules of Active perception and the Action Modules in Brooksian Robotics

Different Types of Modules. In systems of active perception, quasi-functional modules differ from quasi-action modules in that these two types of modules are realised by different computational algorithms and subserve different tasks. In later discussions we will given an account of how these two types of modules differ. Briefly, the quasi-functional modules (such as Snake and the Kalman filter) subserve systems of tracking, while quasi-action modules (such as Adept) subserve planning.

However, such a distinction is not entirely clear-cut, because of their mutual support. On the one hand, fast tracking can facilitate planning. For example, the dynamical Kalman filter adopted in Dickmanns' car is basically a module for tracking; but, the effective and efficient tracking of different perceptual features make it practically possible to maintain planning across a variety of perceptual features. On the other hand, planning may support tracking. For example, the attentive control of saccades is basically a module for the planning of saccadic movements, which is a component of gaze control. Because gaze control subserves tracking, the planning of the attentive control of saccades, in turn, contributes to tracking.

Basic Components of Active Perception cf. Those of Brooksian Robotics. Note that both the quasi-functional modules and quasi-action modules are *basic components* of the active perception implementations. Here, it is worth comparing the basic components of the active perception implementations with those of Brooksian robotics. The automata *wander* and *avoid* in Brooks' three-layered robot and the automata *Stroll*, *Avoid*, *Align* in Mataric (1990), are *action* modules, as we previously discussed (see Section A.2, page 348). The difference between the quasi-action modules and action modules rests on the *computation* of factorial conditions, be they critical variables in Adept, iterative (numerical) transformations of perceptual inputs in tracking mechanisms, visual features in attentive control of saccades, or visual features in the pursuit mechanism. By contrast, the initiation of the above Brooksian robotics action modules need not be further subject to the computation of certain variables, but is caused directly during robots' situated activities. At this point we can see the action control of active perception, compared to the control in Brooksian robotics, as being more highly differentiated and more subtly manipulated.

One might inquire as to whether there are also quasi-action modules built into Brooks' three-layered robot. The answer at first appears to be 'Yes', because the priority control in Brooks' three-layered robot – the functionality of the third layer – seems to consist of quasi-action modules, as is evident in its two automata *integrate* and *pathplan* (see Section 2.3, page 32). Like the quasi-action modules previously discussed, those automata do not in themselves give rise to motor actions but serve to control actions produced by the lower two layers.

The true answer to this question, however, is 'No'. The main reason is simply that those two automata do not manage the computation of certain variables. Instead, they serve to suppress a certain layer and consequently push another layer to continue its operations. The suppression and the 'sanction' for continuation consists of modifications over the 'likelihood' of initiating different layers, according to the pre-fixed priority over the functionality of different layers. The functionality of the third layer may be conceived of as a pre-fixed priority over the tendency of executing different layers. It is a matter of distribution over directly initiated values. There is no computation of any variable. Hence, the third layer in Brooks' three-layered robot does not in fact consist of quasi-action modules. To understand it intuitively, the control in Brooksian robotics is neither highly differentiated nor subtly manipulated as would be expected in the quasi-action modules of active perception implementations.

on the basis of the foregoing discussions we can identify the basic components in the designs of active perception implementations in terms of quasi-functional modules and quasi-action modules. These two types of module have a far-reaching impact on the understanding of emergence in autonomous agent research, as we will see. In later discussions, we will compare the basic components within different strategies of autonomous agent implementation, specifically: Brooksian situated robotics, Steels' exploitation control, Maes' exploitation control, and active perception.

5.4.3 Exploitation on the basis of Quasi-functional Modules and Quasi-action Modules

Exploration and Exploitation. Exploration and exploitation, as we previously discussed (see Section 2.4.1, page 38), are two strategies of action selection for active systems. Regarding exploration, organisms inspect/explore the aspects of the environment most relevant to the required tasks, by arranging the action modules of the systems in parallel or with certain serial orders. Exploitation, by contrast, is needed for bringing explorative activities into *focus*, in the sense that those activities thereby become highly relevant to the required tasks, with the effect of improving the effectiveness and efficiency of those activities. As a consequence, exploitation takes the form of task-specific utilities that serve as constraints in the internal states of active systems in support of the explorative activities in the environment.

Four Types of Exploitation. Four types of exploitation were previously found in the implementation of active perception. They can be seen as task-specific utilities. First, mechanisms of making judgement under uncertainty, such as the Kalman filter, as adopted in tracking systems. Second, various templates of object activities, which are constraints on the spatial invariance and temporal continuity of certain object activities, are incorporated into tracking systems; visual pursuit, in particular, is consequently effective and efficient. Third, dynamical systems incorporated into tracking systems, with the effect of enhancing the capabilities of tracking fast moving targets efficiently. Fourth, the automatic planning of explorative activities, such as the route planning of Adept and saccadic movements. Explanatory exploration, demonstrated by Allen and Bajcsy (1985), is an interesting case of autonomic planning. The explorative activities are controlled for detecting the need of *complementary* information, which may even be information across modalities, in support of the required task.

We can see the quasi-functional modules and quasi-action modules as modules that give rise to aforementioned *task-specific* utilities. Each such modules may serve to accomplish several tasks, but such modules are by no means task-neutral (general-purpose) modules. This point is not hard to appreciate, for those quasi-functional modules and quasi-action modules do not serve to give rise to functional descriptions but relate closely to certain specific (perceptual) tasks. For example, the Kalman filter subserves visual tracking, attentive control of saccades serves to give rise to guidance for saccadic movements, and the computation of critical variables in Adept serves to bring about guidance for the robot to approach the target gradually. Each quasi-functional module or quasi-action module is dedicated to providing task-specific utilities that facilitate the accomplishment of certain specific tasks.

5.5 The Relationship Between Quasi-form Modules and the Exploitative Control of Active Perception

5.5.1 Two Enquiries

Given that the basic components of active perception implementations/systems are quasi-functional modules and quasi-action modules, a straightforward question arises:

A General Question about the Merit of Quasi-form Modules – by identifying task-specific utilities. What specific computational advantage do quasi-form modules provide, as opposed to functional modules and action modules?

Note that the aforementioned quasi-form modules are components of active perception systems, as opposed to other behaviour-based systems. To answer the above question we need first to draw a distinction between active perception systems and other behaviour-based systems.

Autonomous Agents are Necessarily *Active* Systems but May Not be *Perceptual* Systems. Note that both the autonomous systems in Maes (1990b) and those in Steels (1990a) are *active* systems for carrying out tasks of bodily actions, basically because such systems interact with the real environment by bodily actions and maintain exploration and exploitation – two strategies of *action selection* (see previous discussions in Section 2.4.1, page 38). In these systems the availability of perceptual information is presumed. There is no need to arrange further perceptual activities to make available the information needed for certain required tasks. Hence they are not systems of active *perception.* The tasks of such systems, unlike the tasks of active perception systems, are to carry out bodily actions, not to provide *perceptual guidance* for bodily actions. On this point, systems of active perception differ from other systems of autonomous agents.

In the light of the above-mentioned difference, the general question posed above can be re-shaped as: how do the quasi-form modules contribute to *activeness*? Specifically, the question is how the quasi-form modules make systems of active *perception* work, as opposed to the control strategies of other behaviour-based systems? The focus of discussion is on resolution of the question: how do the active systems differ from other autonomous agents in their respective maintenance of exploration and exploitation.

Two Enquiries. It is not difficult to see that the general question about quasi-form modules (how do the quasi-form modules make systems of active perception work, as opposed to the systems of autonomous agent in general?) concerns *explanation* of the relationship between quasi-form modules, task-specific utilities, and activeness, as opposed to further *description* of present active perception implementations. This relationship can be encapsulated in two enquiries:

> **First Enquiry.** *How* can quasi-functional modules and quasi-action modules, by means of providing those four types of task-specific utilities, serve to improve the effectiveness and efficiency of active systems?

Relating to this question, we can consider a corresponding question:

> **Second Enquiry – Concerning the Reason for the *Form* of Quasi-form Modules.** Why does the improvement of effectiveness and efficiency in systems of active perception, which is facilitated by the four types of task-specific utilities, take shape in the form of *quasi*-functional modules and *quasi*-action modules?

Resolutions of these two enquiries (about the relationship between quasi-form modules and task-specific utilities) together constitute the explanation of quasi-functional modules and quasi-action modules with regard to their contribution to activeness.

5.5.2 First Enquiry: How Quasi-functional Modules and Quasi-action Modules Contribute to Active Perception.

Let us begin by dealing with the first enquiry about the quasi-form modules and the four types of task-specific utilities, and their contribution to activeness: specifically, how do those four types of task-specific utilities help to answer the question of what makes active perception systems work?

Here, we must enter a caveat: mere task-specific utilities do not *suffice* to bring about activeness. Rather, they stand as *facilities* for exploratory modules, which are necessary conditions of activeness. For example, the attentive control of saccades facilitates saccadic movements by providing their guidance, while the motor capabilities of saccades must be available beforehand. For gaze control, the mechanisms of binocular vergence are also necessary.

The status of the aforementioned task-specific utilities is not hard to appreciate from a conceptual perspective. As mentioned previously (see Section 2.4.1, page 40), exploitation *presumes* the implementation of exploration, because exploitation serves to make use of *constraints* in the internal states of active systems, in support of the explorative activities in the environment. Those task-specific utilities serve as *constraints* on explorative activities. The constraints *per se* are not the necessary conditions of activeness.

The contribution of the aforementioned four types of task-specific utilities to activeness can be understood via the idea of: *guidance* for fetching *further needed* information in support of the required task. Without such guidance, the explorative activities would be pointless and the required task would consequently be difficult to accomplish. On the basis of this idea, the aforementioned four types of task-specific utilities can be further understood in terms of their consequences for providing guidance.

Judgement under Uncertainty. It is obvious that making judgements under uncertainty is necessary for real-time response in a tracking system. Note that successful tracking needs the selection of sensory-motor activities in a *serial* temporal order. Because of the serial order, as soon as the tracking system fails to respond promptly to keep track of its target, it may consequently lose that target permanently.

There is no spare time for judgement, yet the tracking system must provide perceptual information about the target to derive the needed information for its tracking at the next moment. For example, a rapid judgement of a possible shape can facilitate the derivation of relating predictions by seeking support from relating templates. The rapid judgement provides appropriate guidance for a real-time response, so that the tracking system can have the needed time to direct sensory organs toward the likely location at the next moment.

Using Templates. The incorporation of templates in tracking mechanisms reflects the spatial invariance and temporal continuity of certain particular target movements. The tracking mechanisms, such as the control of the pursuit movement (see Section 3.4.5, page 104), take advantage of such templates by easily moving the fovea to the foreseen position of the target at a short period of time later. The tracking mechanisms would not lose track of the target and can thus more easily fetch the perceptual information at the next moment. Not only the position at the next time moment, but also the shapes of deformable targets (such as a cell or fingers), can be foreseen. Those templates provide the tracking mechanisms with many facilities to arrange their internal states in order to simulate the tracked targets at the next moment, and consequently such mechanisms can respond promptly to continue their tracking of the target.

Given the above, the templates of a tracking system serve as guidance for making it easier to fetch perceptual inputs at the anticipated locations: the needed information at a later moment.

Using Dynamical Systems. The incorporation of dynamical systems in a tracking system, as in the implementation of the dynamical Kalman filter in Dickmanns' car, makes the tracking systems respond promptly and the system of active perception can thus have enough time to manage further processes.

The impact is similar to the judgement under uncertainty and the adoption of templates. The incorporation of dynamical systems facilitates the tracking system by providing guidance for promptly fetching the needed information for further tracking at a next moment (e.g. at the next frame time). Different guidance will be provided in different circumstances, and thus the required task can be carried out smoothly.

Planning of Actions. Serial order is no less important than tracking in the tasks of planning. The effective computation of critical variables, such as $\mathbf{T}$, $\mathbf{r}$, $\mathbf{N}$, κ_n, τ_g, determines that Adept can derive certain geographical paths step-by-step. The computation of a certain variable is important for deriving the appropriate geographical path that Adept needs in its particular circumstances.

The planning is stepwise, and hence specific guidance is needed for Adept in specific circumstances. If this guidance is not provided promptly, the robot would need to seek another route; otherwise it would be stuck. The computation of those critical variables at the right time can ensure the availability of a previously planned route. The effective and efficient computation of a certain critical variable can ensure the computation of the further needed critical variables for maintaining the same route. A certain module would serve as guidance for fetching further needed information and computing further needed critical variables.

As another example, the detection of the need for *complementary* information in Allen and Bajcsy (1985) also serves as guidance for pushing forward the computation of relevant features of the targeted object. If the robot does not shift its control from visual computation to seeking haptic information, it would be pointless for the robot to recognise the curvature of the transparent surface. The robot would be likely to get stuck, and consequently the recognition of the target object would be impossible. Detecting the need for complementary information, hence, is a crucial guide for fetching the further needed information.

It is worth noting that Adept does not derive the aforementioned guidance on account of a pre-specified detailed world model of relations between the target, the obstacles and the robot itself. Rather, its derivation of guidance is subject to the spatial and temporal unpredictability of obstacles (see Section 4.2.1, page 126; see also the theoretical background in Section 2.3, page 34). Despite this unpredictability, Adept can still provide guidance as to where lies the freespace leading to the target, by taking advantage of the occlude effect detected in the direction toward the target (see Figure 4.5). This example suggests that the guidance provided by quasi-form modules has taken account of environmental unpredictability, and hence the active perception systems can respond to the circumstances of the *real* environment.

The above discussion shows that the quasi-form modules contribute to activeness by providing guidance for the information needed for the required tasks (hence answering activeness), as manifested in the four types of task-specific utilities. Thus, the discussion answers the aforementioned first request as to the relationship between quasi-form modules, task-specific utilities, and activeness.

The second enquiry about this relationship will be discussed in the next section.

5.5.3 Second Enquiry: Why does Active Perception Need *Quasi*-functional Modules and *Quasi*-action Modules

Here, we begin to consider the second enquiry, which concerns the aforementioned relationship:

> Why does the improvement of effectiveness and efficiency in systems of active perception take shape specifically in the form of *quasi*-functional modules and *quasi*-action modules?

What sort of Answers do We Expect? The topic here is not evolutionary explanation, consequently we will not consider the evolutionary processes that lead to *quasi*-functional modules and *quasi*-action modules, in contrast to functional modules and action modules. Nor will we seek empirical explanations as to why evolution ends up with the *current* quasi-functional modules and quasi-action modules, as opposed to *other* quasi-functional modules and quasi-action modules. Rather, we seek *comparative* conceptual explanations as to why it is quasi-functional modules and quasi-action modules that suit active perception. Why it is not, alternatively, the functional modules in Marr's theory of vision or the action modules in autonomous agent research that suit active perception? An intuitive answer can be neatly shaped in the form of an exclusive demand – that activeness (i.e. what makes active perception work) needs *quasi*-functional modules and *quasi*-action modules.

We need not maintain that it is impossible to accomplish activeness without those quasi-functional modules and quasi-action modules. The action modules in autonomous agent research may well accomplish activeness, from a theoretical point of view. However, evolution opts for *relatively optimal* solutions among candidates. We only need, hence, to show that quasi-functional modules and quasi-action modules are *better* suited to activeness, compared to other modules. Intuitively, it can be expected that those quasi-functional modules and quasi-action modules are better than the alternatives because of certain outstanding properties, which satisfy certain crucial requirements of active perception.

From Requirements in Ethology to Requirements in Computational Machinery. Compared to behaviour-based systems in general, active perception systems require *subtler* control of perceptual organs/devices. In autonomous agents the sensory systems need not be active. They are usually simple connections to the action modules, as we have seen in Brooks' three-layered robot, Mataric (1990), Maes (1990b), Steels' rock collection robots (1990b) and his robot with the control of geographical representations (1990a). In other words, the availability of perceptual data for the required tasks is presumed. Yet, this is the very topic for the systems of active perception. Unlike other autonomous agents, the robots with active perception systems do not simply deal with the randomly available perceptual inputs which are collected in their bodily interactions with the environment. Rather, they must estimate the needed information for their perceptual tasks in support of their bodily activities in the real environment.

The most salient bodily activities are those for survival, as is argued in ethology. For such salient bodily activities, *relevant* perceptual information must be collected, such as that supporting the foraging activities of predators, and that needed for prey to flee swiftly. These perceptual systems, presumably, need to maintain tracking, scene understanding, categorisation, and the learning of all the above perceptual abilities. An important question about these ethological requirements is their connection to the machinery of perceptual systems – whether such ethological requirements impose certain constraints on the construction of the machinery of perceptual systems. Three requirements on the machinery in question can be derived from the above characteristics of survival in the real environment.

1. **Stepwise and Iterative Processing.** An intriguing phenomenon of perception has been listed as one of two requirements of task identification: the stepwise and iterative processing of perception, such as the attentive control of saccadic movements. That is, the foveae must be directed iteratively and promptly toward important features, which are not made available simultaneously as batch information, but are derived stepwise, i.e. information at a later step depending on what has been made available and evaluated in earlier steps.
2. **Prompt Response.** In addition, the perceptual processing in real-time is typically necessary for survival. Perceptual processing must be highly flexible. Animals, for survival, must compete for speed. At this point, time is very critical. Perceptual systems need to collect data sparsely, given their limited computational resources, and make judgement under uncertainty.
3. **Accurate Recognition of Fast-changing Shapes.** Furthermore, for accurate responses in foraging behaviour, fighting and fleeing, animals must also be able to recognise fast-changing shapes accurately.

Above are three positive requirements, while below is a negative requirement.

4. **Not Entirely Reliant on Pre-programming, Because of the Complex and Unpredictable Environment.**

> Bear in mind that the environment is highly complex and somewhat unpredictable. The machinery in question, consequently, must respond well to environmental complexity and unpredictability. Given

that the computational resources are sparse, it would be pointless for perceptual systems to *pre*-programme (on the basis of functional specification) *all* possible perceptual shapes and categories and the consequently required sensory-motor and bodily movements, as is gradually realised in mobile robotics. The lesson, in general, is that the environmental complexities are hard to tackle, and too much time spent in searching huge databases makes the design futile.

In the complex and unpredictable environment, it is also pointless to pre-determine the information needed in every circumstance for carrying out a specific task. For example, there is no entirely fixed route for the saccadic movements of similar tasks in various circumstances. There is also no fixed arrangement of operations for controlling a car in the vehicle.

Requirements of Task Identification and Process Arrangement. Discussion in this chapter so far has derived several requirements. Apart from the recent three positive and one negative requirements, previous sections about task identification and process arrangement also worked out certain requirements, briefly listed as follows:

- **Two Requirements for Task Identification.** As previously discussed (page 156), the machinery of task identification must address the tasks provided either by intention systems *outside* the perceptual system, or by the exploitative cues *within* active perception systems, such as the prey's cues for swift fleeing. In addition, tasks are identified gradually by active perception systems through iterative exploitative control.
- **Two Requirements for Process Arrangement.** Previous discussions (page 160) indicate two requirements about the machinery of process arrangement. First, the machinery of process arrangement for an operation-specialist system must be based on *small* architectures. Second, a combinatory operation-specialist system should expand from small operation-

specialist (sub-)systems, on the basis of two categories: inter-system links or within-system relational structures.

An Analysis about the Connections between these Requirements and the Nature of Quasi-form Modules. Do the requirements derived so far connect somehow to quasi-functional modules and quasi-action modules? Specifically, this question seems to relate closely to another question: can the above requirements of active perception be fulfilled *exclusively* by quasi-functional modules and quasi-action modules, but not by functional modules or action modules?

This question specifically relates to a further consideration about the nature of quasi-form modules: does the *nature* of quasi-form modules make them *exclusively* suited to the above requirements? This question concerns *how* that specific nature can make the quasi-form modules exclusively suit the above requirements.

According to previous discussions, the nature of those quasi-form modules comprise (1) the *indirect* contribution to functional descriptions and to the control of bodily actions (see Section 5.4.1, page 176), and (2) the production of *guidance* for fetching *further needed* information in support of the required tasks (see Section 5.5.2, page 186). The above 'how' question can accordingly be re-shaped briefly as follows: does the fulfilment of the above requirements (of active perception) need to take advantage of these two characteristics of quasi-form modules (i.e. (1) and (2))? This question is tantamount to an inquiry about whether activeness must be grounded on the above characteristics (1) and (2).

The argument in the next section will show that activeness must be so grounded. When this is confirmed, it is straightforward to confirm also that active perception must take the form of quasi-form modules.

5.6 Bridging Activeness and Quasi-action Modules with Dynamic Small Modules

This section argues for an affirmative answer to the last point (hypothesis) drawn in the last section – thus, it is argued that activeness must be grounded on the aforementioned characteristics (1) and (2) of quasi-form modules. The argument will straightforwardly lead to an answer to the second enquiry raised previously, which was a request for providing explanation as to the *form* of quasi-form modules.

The general strategy of argument is as follows. The argument begins with a novel notion – dynamic small modules – which serves to encapsulate all the requirements of active perception listed in the previous section. With this notion, we then argue that this notion is grounded on the above two characteristics (1) and (2).

Defining the Notion of Dynamic Small Modules. The requirements of active perception listed in the previous section can be summarised with the notion of *dynamic small modules*, which means the simple modules with dynamic combination in single small operation-specialist systems that have the following two additional characteristics: (a) such modules maintain stepwise and iterative processing to confirm gradually the external enquiries (i.e. perceptual tasks) in the real environmental conditions; (b) such modules can grasp and keep track of fast-changing shapes accurately.

The following two subsections argue respective that quasi-form modules *can* fulfil the notion of dynamic small modules, on the one hand, and that functional modules and action modules *cannot* do that, on the other. To put it briefly, the notion of dynamic small modules (which has characteristics (a) and (b)) is exclusively grounded on quasi-form modules (which have characteristics (1) and (2)).

A Conceptual Analysis. Before we discuss this statement, we must resolve a worry, that dynamic small modules and the quasi-form modules (i.e. quasi-functional modules and quasi-action modules) seem to be conceptually identical. If so, then dynamic small modules are neither functional modules nor action modules for an *a priori* reason: quasi-functional modules and quasi-action modules are defined as being neither functional nor action modules. Our discussions would consequently be trivial.

However, dynamic small modules and quasi-form modules are conceptually different. The concept of dynamic small modules is well specified via five characteristics – namely, basic perceptual features, dynamical combination of modules, various specialist sensory movements which are situational, stepwise sensory-motor movements with evaluation in each step, and the generation of perceptual capabilities in situations. In contrast, the concept of quasi-functional modules and quasi-action modules is a *negative conception* about modules – modules that contribute to functional descriptions *indirectly* and those that provide *guidance* of sensory-motor movements without being identical to (sensory-motor) actions.

The concept of quasi-functional modules is exemplified by the Kalman filter and Snake, which manifest certain characteristics of dynamic small modules, such as flexible and quick mechanisms of feature integration. However, such characteristics are not included in the concept of quasi-functional modules. In addition, the concept of quasi-action modules is exemplified by the computation of critical variables in Adept, which manifests certain characteristics of dynamic small modules, such as the stepwise movements with evaluation in each step. Yet, such characteristics are not tantamount to the leading concept of quasi-action modules – perceptual guidance of sensory-motor movements. Within the conception of perceptual guidance, there is basically no constraint about what guidance there should be and how to work out the guidance. Yet, the conception of dynamic small modules strongly circumscribe what guidance there should be for active perception. Thus, the concepts of dynamic small modules and quasi-form modules are distinct.

One might raise a further objection by contending that drawing a distinction between dynamic small modules quasi-functional modules and quasi-action modules is trivial because the supposedly different concepts might end up the same. These two notions may be ultimately identical, like two concepts of triangle – three-sided polygon and three-angled polygon. If this objection is tenable than the current plan of argument would end with reformulation of the concept of quasi-form modules.

The notion of dynamic small modules is indeed *not* simply a reformulation of the quasi-form modules, as evident in two points. First, the proof that two geometrical notions are equivalent is usually not trivial. Although these those two notions may indeed be equivalent, it may be hard to realise. In fact, a proof may need significant intellectual efforts. Second, the sources of these two notions are different, as previously argued. One arises from the requirements of active perception, as a psychological capacity/faculty, while the other arises from the descriptions of its actual implementations. Strictly speaking, neither of these two notions is simply a reformulation of the other. Even the most obvious overlap between these two notions – stepwise and iterative processing (as manifested in the attentive control of saccades) – is not a mere conceptual reappearance: the emphasis of it in the definition of quasi-functional modules is not to highlight stepwise and iterative processing *per se* (which is a requirement of dynamic small modules) but to stress the importance of the transformation of values for providing guidance. Any success really needs substantial understanding as to the linkage between psychological capacities and computational paradigms. This is also the case for the following argument.

5.6.1 Quasi-form Modules *Can* Fulfil the Notion of Dynamic Small Modules.

A Reminder about the Modules with the 'Quasi-' form. Now, we are about to consider whether the notion of dynamic small modules can be realised in the form of *quasi*-functional modules and *quasi*-action modules. Before we discuss this topic, it would be useful to recall our definitions of quasi-functional modules and quasi-action modules (see Section 5.4.1, page 176).

The quasi-functional modules are understood as modules that do not in themselves produce functional features of perception but still have a bearing on the resulting functional control: the factorial conditions contribute indirectly to functional descriptions (see our previous discussions in Section 2.4.4, page 57). Specifically, those factorial conditions *substantiate* the iterative (numerical) transformations of perceptual inputs (as is evident in tracking systems, such as Snake and the dynamical Kalman filter).

By contrast, quasi-action modules are defined as modules that provide other kinds of factorial condition, namely guidance of sensory-motor movements; thereby, such modules contribute *indirectly* to (sensory-)motor *actions* because guidance is not tantamount to actions. Specifically, such factorial conditions constitute action control (i.e. guidance) of sensory-motor movements, *without specifying exactly* what such motor actions are.

In Section 5.4.1 (page 176), we provided three examples of quasi-action modules: the computation of critical variables (as in Adept), the computation maintained in the attentive control of saccades, and the mechanism of visual pursuit. All of these three examples relate to the guidance of sensory-motor movements, but none of them alone is sufficient to specify a mechanism of (sensory-)motor action.

Requirements on a Legitimate Argument. Here, we argue that the notion of dynamic small modules can be realised in the form of quasi-functional modules and quasi-action modules. Note that the dynamic small modules are *requirements* of activeness, while we have contended that quasi-functional modules and quasi-action modules (as opposed to functional modules and action modules) are the very mechanisms underlying the present active perception implementation. Accordingly, the following arguments are required to show two points regarding the relationship between that above ideal notion and the underlying mechanisms.

The first is that the notion of dynamic small modules as characterisation of active perception *can* be realised in the form of quasi-functional modules and quasi-action modules.

This point must be discussed. If the notion of dynamic small modules, as requirements of active perception, *cannot* be realised by quasi-functional modules and quasi-action modules – the mechanisms that we see as underlying active perception – then such requirements cannot be realised at all. Consequently, it means that such requirements may be purely theoretical, in that no mechanisms insofar as we know can realise it. Fortunately, we will show that the dynamic small modules can actually be realised by the mechanisms that we interpret as being the underlying mechanisms of active perception – quasi-functional modules and quasi-action modules.

The second point is that quasi-functional modules and quasi-action modules *suffice* to realise that ideal notion. The second point needs to be discussed apart from the first point, because the quasi-functional modules and quasi-action modules may simply be *necessary* conditions of carrying out the ideal notion in question without being sufficient conditions as well. That is to say, there might be certain modules of another type which are needed for the realisation of that ideal notion.

When we have achieved these two points, we can infer that the dynamic small modules (as an ideal notion of active perception) *must* take shape in quasi-functional modules and quasi-action modules (as the mechanisms that we interpret as the underlying mechanisms of active perception). In later discussions we will show that such an ideal notion cannot take shape in *other* types of modules, which are the types of modules attended to so far in relation to the perception-action relationship. Accordingly, if the dynamic small modules *can* be realised in the form of quasi-functional modules and quasi-action modules, then they *must* be realised in this way.

The Dynamic Small Modules Realised in Quasi-functional Modules and Quasi-action Modules. According to previous discussions, quasi-functional modules, in short, are modules whose production of functional descriptions is *subordinate* to the bodily actions which relate to the required tasks. Functional descriptions are not provided simply because perceptual systems serve to provide perceptual features, but are produced *insofar as they are needed* for guiding certain bodily actions.

By contrast, quasi-action modules are those that provide *guidance* (in the form of perceptual information) for sensory-motor movements, while that guidance *per se* is not tantamount to a mechanism of movements/actions. For the effectiveness and flexibility of that guidance, there are basically no constraints imposed on it. Anything needed to guide sensory-motor movements can be computed by appropriate (specialist) mechanisms, such as the mechanism for the attentive control of saccades. In particular, the guidance can be stepwise with evaluation in each step, as demonstrated by the attentive control of saccades and the gradual movements of Adept between obstacles toward the target behind those obstacles.

On the basis of the quasi-functional modules described above, the notion of dynamic small modules (see Section 5.3.2, page 161) can be *fully* realised, as shown in the following discussions about the itemised five requirements of the dynamic small modules. Notice that we aim to show that quasi-functional modules and quasi-action modules not only can but also *suffice to* realise the notion of dynamic small modules.

Simple Modules with Dynamic Combination in Single Small Operation-specialist Systems. Quasi-functional modules and quasi-action modules can be organised into operation-specialist systems, as already demonstrated in the implementations surveyed in chapters three and four. All the implementations we surveyed consist of quasi-form modules, on the one hand, and all such implementations *are* operation-specialist systems, on the other.

In addition, it is also the case that the quasi-form modules in those implementations can be combined by dynamic mechanisms, as demonstrated by three dynamic mechanisms – the energy control of Snake, the dynamical systems in the dynamical Kalman filter, and the dynamical systems in Dickmanns' car. Dynamical systems serve as dynamic combinations of quasi-form modules.

Those dynamic mechanisms contribute to the generation of perceptual features only indirectly, but they indeed serve to manage the dynamic combination, for quick and flexible combination.

Additional Characteristic (a) – maintaining stepwise and iterative processing to gradually satisfy the enquiries raised from outside perceptual systems. It is required in the notion of dynamic small modules that the determination of sensory-motor movements must be stepwise with evaluation in each step, to porvide a flexible response to current situations in the unpredictable environment.

This is generally not difficult for quasi-action modules, which provide guidance for sensory-motor movements. As just mentioned, there are no constraints imposed on such guidance. Like the computation of critical variables, the stepwise control with evaluation in each step can be seen as a particular means of guidance, which can be made available by a specialist mechanism. For example, the saccadic movement is maintained by the attentive control of saccades, which is a specialist mechanism.

With such stepwise and interactive processing, the external enquiries can be gradually supported by relevant perceptual information which is collected by comparing the information already made available and the information still needed for satisfing those enquiries.

Additional Characteristic (b) – Grasp and Keep Track of Fast-changing Shapes Accurately. As the notion of dynamic small modules requires, the basic perceptual features must reflect the most important (relevant to tasks) constituents of perceptual experience, such as lines and curves. Note that such features are usually managed under time pressure for the required tasks, hence they must be highly selective.

Such basic perceptual features can be provided by quasi-functional modules, for the computation of the quasi-functional modules is highly selective of what is needed for the current situations. Specifically, those perceptual features can be provided by the computation of critical variables, which is indeed highly selective, as exemplified by Adept, which only computes the variables needed for moving (via a relatively short path) toward the target. Alternatively, the perceptual features can be obtained via the *transformations* made available by the Kalman filter, which provides the relevant features to the perceptual situations. Note that a particular algorithm of the Kalman filter presumes limited knowledge (see Section 4.1.2, page 119). Perceptual inputs are consequently transformed into perceptual features which are relevant to the current situations.

Furthermore, quasi-functional modules and quasi-action modules can grasp and keep track of fast-changing shapes accurately, as demonstrated by the dynamical Kalman filter (see Section 4.1.3, page 122) and Dickmanns' car (see Section 4.2.2, page 132). Although tracking is subject to serious time pressure, thanks to dynamical systems the above implementations are successful.

5.6.2 Functional Modules and Action Modules *Cannot* Fulfil the Notion of Dynamic Small Modules.

In contrast to the above argument, the next step in the overall argument is to show that the notion of dynamical small modules cannot be realised by functional modules (like those in Marr's theory of vision) or action modules (like those in Brooksian robotics and Maes (1990b)) (pages 175-183). Notice that the following argument concerns the *sufficient* conditions for implementing active perception. The aim is to show that the implementation of active perception would not be complete *without* quasi-form modules. Accordingly, the adoption of functional modules or action/competence modules itself will not cause a problem, if apart from that certain quasi-form modules are also adopted to implement active perception.

Dynamic Small Modules Cannot be Functional Modules or Action modules. The reason is intuitive, namely that neither functional nor action modules manifest the characteristics of dynamic small modules, while the quasi-functional modules and quasi-action modules do actually manifest those characteristics. The notion of dynamic small modules, accordingly, must be realised in the form of quasi-functional modules and quasi-action modules. In the following discussions we see support for such an argument in different computational methodologies: the Marrian theory of vision, Brooksian robotics, Steels' exploitation, and the control of energy spreading in Maes (1990b).

Functional Modules in Marrian Theory of Vision. The functional modules characterised in Marrian theory of vision extract perceptual properties via a non-dynamic hierarchical order of information processing, without any dynamic processes. Hence, the combination between modules is apparently not dynamic. Furthermore, those functional modules are not the *small* modules we previously defined, because they do not generate perceptual categories in situations, but instead pre-determine them. Hence, the dynamic small modules cannot be realised in the form of such functional modules.

Action Modules in Brooksian Robotics. The dynamic small modules cannot be shaped in the action modules in Brooksian robotics, either. This is because Brooksian robotics does not have memory for internal representations (be they language-like or distributed) and consequently does not encode categories. In addition, although sensory-motor connections, in principle, can be implemented on the basis of Brooksian robotics, such connections do not suffice to maintain the internal computation of active perception. For example, it is unclear how the basic features, such as lines and curves, can be provided directly by sensors without the mediation of computation, as seen in the computation of various kinds of Kalman filter.

Furthermore, even if those basic perceptual features can be made available, the smooth combination between perceptual features remains a difficulty for the subsumption architecture of Brooksian robotics. For example, the internal continuity of Snake does not seem to be simply a matter of suppression between simple automata, which is maintained by the top layer of Brooks' three-layered robot. Hence, the action modules in Brooksian robotics do not suffice to realise the notion of dynamic small modules.

Action Modules in Steels' Exploitative control (1990a). The action modules in Steels' exploitative control, as introduced in Section 2.4.3 (page 49) seem to be the software simulation of Brooksian robotics in terms of geographical representations. We can see those representations as being 'upgraded' from Brooksian simple automata (such as *avoid* and *wander*): 'upgraded' because such internal representations function like reactive agents[14] without mentioning dynamic combination between modules – e.g. situational *modifications* of goals. This is because there are basically no control mechanisms responsible for modifications.

Furthermore, there is no ground in Steels' (1990a) to realise the stepwise control of sensory-motor movements with evaluation in each step. The interactions between those geographical representations are based on strict counterparts of the external world. That is, there is no further evaluation of the relative importance of those representations, nor is there any transformation between the readily encoded geographical representations (such as the transformation in Snake and the Kalman filter). Because there is neither evaluation nor transformation, Steels (1990a) does not suffice to realise the notion of dynamic small modules.

Action Modules and Functional Descriptions in Maes (1990b). The exploitation of internal representations maintained in Maes (1990b), as previously discussed in Section 2.4.4 (page 53), includes subtle control over action modules, which is substantiated by links between goals, energy spreading via links, thresh-

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[14] In fact, Steels (1990a) describes the implemented modules, which carry out the geographical representations, in terms of 'agents'.

olds of action modules, and global parameters (such as γ and ϕ). Such a style of exploitation seems to be likely to fit the description of dynamic small modules, because the exploitation is flexible. Specifically, evaluation between global goals (i.e. the actions specified in those action modules) is maintained by responding to current situations, and those global goals are subject to modifications (over their activation energy). Thus, Maes' exploitative control seems to be promising in performing the dynamic combination between action modules.

An apparent problem is that the aforementioned action modules are all pre-specified, i.e. encoded by hand. In addition, they are qualitative language-like representations.[15] Such qualitative representations do not seem to suit the factorial conditions of perceptual features, as shown in the Kalman filter.

Perceptual features might be shaped in the form of analogical representations, as Steels suggests. They can also be shaped with iterative transformations, such as those found in the Kalman filter. However, the (qualitative) language-like representations are a long way from appropriate representations.

An objection might be raised by contending that the competence/action modules in Maes (1990b) do not purely serve to *represent* perceptual features, but indeed serve as *action* control, especially the dynamic combination between action modules. However, this type of action control does not help the competence modules to suit the notion of dynamic small modules, because sensory-motor movements (which can be seen as actions) seem more likely to be controlled in the form of factorial conditions (which are numerical) than in language-like representations. It would be pointless to implement the attentive control of saccades in language-like representations, because the evaluation of fine-grained perceptual features and the comparison between such evaluations is a matter of numerical control. Furthermore, the stepwise computation of (perceptual) critical variables,

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[15] It is arguable that numerical representations *can be* seen as language-like representations because numerical codes can squarely be translated into (language-like) propositions. Yes, they can be so translated, but the contrast between numerical and language-like representations in this sense is trivial. The term 'language-like representations' used in the following argument is not referred to the propositions in this sense. They are, instead, meant as *qualitative* representations of non-numerical representations, as demonstrated by the descriptions in the condition-list '(hand-empty, sander-on-table)' (see Section A.2, page 347).

as needed by Adept which is designed for the planning of bodily actions that support sensory-motor movements, cannot be supported in Maes' exploitative control. No (numerical) computation of such variables is feasible with language-like representations, let alone the stepwise control over the computed values. Thus, when the computation of (perceptual) critical variables is needed for sensory-motor movements, it stands as a difficulty for the control seen in Maes (1990b).

Reconsideration of the Contrast between Numerical and Language-like Representations. A further objection may be raised, that perceptual representations can *in principle* be transformed into language-like representations[16], and thus the language-like representations do not in themselves constitute a deficiency in implementation.

Three replies: First, the previous argument about the inappropriateness of non-quasi-form modules is about the necessity of numerical representations, not about the deficiency of language-like representations. The problem of the representations in Maes (1990b) is that they (as language-like) could not carry out numerical computation – a requirement for computing factorial conditions. Analogical representations may well be transformed into language-like representations and thereby be computed. However, it is generally not wise to make transformations on certain representations and consequently fail a certain requirement of the computation. If numerical representations work well, there seems to be no reason to transform them into less suitable ones.

Second, numerical representations are not tantamount to analogical representations. There is a clear distinction between them. The computation carried out by the Kalman filter is numerical, but there is no guarantee that the computation is based on analogical reasoning. Indeed, it happens not to be so based. It computes on the basis of the comparison between current knowledge gains and previous expectations (see Section 4.1.2, page 119). There is no indication that such comparison is grounded on analogical reasoning.

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[16] In the debate about the nature of visual imagery between Kosslyn and Pylyshyn in the 1970s-80s, Pylyshyn maintained that analogical representations can *in principle* be transformed into language-like representations and thereby be computed (Tye 1991; Kosslyn 1994)

Last, transformations between representations (such as those between language-like and connectionist representations) are usually grounded on a shift to a different paradigm of implementation (see discussions in Fodor and Pylyshyn (1988)). This is theoretically interesting but may consequently compromise the efficiency of computation. Connectionist representations can be implemented by language-like representations, and vice versa. For example, connectionist computation is mostly implemented in *digital* machines, where certain language-like representations are necessary. Conversely, the PDP can *in principle* serve as an implementation of the computation based on language-like representations, as suggested by Fodor and Pylyshyn (1988). The problem is that the computation may consequently be carried out less efficiently, which is certainly not appreciated. This point has been contended by Churchland and Sejnowski (1992), two connectionists, that if certain tasks are implemented most appropriately by a machine with language-like codes, why bother to transform them into a connectionist machine? The transformation may be theoretically interesting, but the efficiency of computation may be accordingly lost.[17]

In brief, the numerical computation of factorial conditions is not appropriately carried out by language-like representations, hence the language-like representations in Maes (1990b) do not suit a requirement of dynamic small modules, namely computing the perceptual inputs on the basis of factorial conditions.

5.6.3 Summary of 5.4, 5.5 and 5.6

In these three sections we strive to understand the internal control of active perception. Analysis of internal control indicates that the internal control of active perception is maintained by *quasi*-form modules and that such control is ultimately based on four types of exploitative control, in fact four types of task-specific utilities: judgement under uncertainty, using templates, using dynamical systems, and planning of actions. Thereby, the relationship between activeness and the internal control of active perception consists of resolutions of

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[17] Remember that a previous point – the transformation of numerical representations into language-like representations which are less suitable in view of efficiency – is sadly such a case.

two enquiries: first, how such quasi-form modules contribute to active perception (beyond autonomous agents in general); second, why the internal control of active perception needs to take shape in the form of *quasi*-form modules.

The first enquiry is answered by the following two-step argument. First, these quasi-form modules provide the aforementioned four types of task-specific utilities. Second, such task-specific utilities serve to work out the guidance for fetching further needed information in support of the required tasks. With these two steps together, the quasi-form modules lead to the accomplishment of required tasks, and consequently the first enquiry is answered.

In order to resolve the second enquiry, one additional notion is introduced, namely dynamic small modules, which characterises the requirements for the mechanisms of active perception. The general strategy of resolving this enquiry is: active perception requires dynamic small modules, and such modules *must* be realised by quasi-form modules. Argument shows that quasi-form modules can satisfy the requirements of dynamic small modules, while functional modules and action modules cannot. Thus, the second enquiry is resolved.

5.7 Summary

This chapter answers the question of how the control of active perception systems manages to accomplish the required tasks. Analysis shows that the basic components of active perception systems are quasi-functional modules and quasi-action modules. Unlike the components of other behaviour-based systems, these quasi-form modules provide perceptual *guidance* which leads to the accomplishment of required tasks, as manifested in four types of task-specific utilities for exploitation: judgement under uncertainty, using templates, using dynamical systems, and planning of actions.

The relationship between the control of active perception and the above-mentioned quasi-form modules is clarified in the statement that the control/mechanisms of active perception *must* take shape in the form of the above quasi-form modules. Argument justifies this statement by showing that only *quasi*-form modules can satisfy all the requirements for such mechanisms, including: the requirements for task identification and process arrangement, and the four characteristics of the above control asserted in the notion of dynamic small modules. The requirements for task identification and process arrangement are: identifying tasks through iterative processes, and organising a simple or combinatory system on the basis of inter-(sub-)system links or within-system relational structures. The four characteristics of the control of active perception are: stepwise and iterative processing, prompt response, accurate recognition of fast-changing shapes, and no entire reliance on pre-programming (because of the complex and unpredictable environment). With the consideration of so many requirements, argument of this chapter has justified the above statement.

Chapter 6

Principles of Task-level Emergence

This chapter considers the task-level emergence of active perception from three perspectives. Firstly, the understanding of task-level emergence needs certain principles to address different emergent phenomena, from the simple to the complicated: specifically, from the emergence of processes in a simple single operation-specialist system, that seek the accomplishment of tasks, to the emergence of control happening in a combinatory system. Those principles are not to be created from scratch, but instead will be extracted from four present models of life origin, which is the archetype of emergent phenomena.

Secondly, the serial order of stepwise computation manifested in active perception is addressed via the notion of internal cohesion. This notion answers the question of why the quasi-form modules can respond to unpredictable environmental factors, on the one hand, but still maintain effective serial orders between various processes of active perception, on the other.

The third aspect of task-level emergence concerns the relationship between the environment and the functionality of a cognitive system, a relationship currently explained by the philosophical accounts of externalism which emphasise the substantial mediation of the environment, as manifested by Brooks' slogan: the environment is the best model of the world. This chapter considers an alternative perspective, by introducing a notion – inverse ecological niche – according to which the functionality of cognitive systems should reflect the characteristics of organisms' ecological niches in order to support organisms' survival and well-living in their respective ecological niches.

The discussion of this chapter begins with the distinction between task-level emergence and other kinds of emergence.

6.1 Task-level Emergence

The Notion of Task-level Emergence. Emergence is usually understood to occur at larger time scales than that of the task level; for example, ontogenic or phylogenic time. The study of active perception will first add to the understanding of emergence by considering emergence at task-level.

The Existence of Task-level Emergence. Since there are no complete blueprints in place for autonomous systems, the maintenance of factorial conditions (including transformations of perceptual inputs and values of critical variables) and the stepwise guidance of sensory-motor movements cannot be entirely explained in terms of pre-determination. This holds for the stepwise computation of active perception. Given that emergence is understood as the opposite concept to that of pre-determination (see Section 2.6, page 64), it follows directly that the accomplishment of tasks in active perception is a matter of emergence.

It is worth noting that certain phenomena of active perception emerge at the task level – i.e. as events at the time scale of task accomplishment – because the accomplishment of tasks takes place without input from learning or anything else gained beyond the task time (e.g. phylogeny). In fact, the implementations we reviewed in chapters three and four can be understood independently of learning with regard to their respective strategies of accomplishing the required tasks. The derivation of guidance in support of bodily actions is entirely maintained at the task level. The emergence of that guidance, thus, is an event at run-time. Hence, it is clear that the emergence of adequate guidance for accomplishing the required tasks of active perception occurs at the task level.

The Context of Emergence is Needed. If we are completely attached to the context of pre-determination, the derivation of adequate guidance in active perception would become difficult to explain, because perceptual processes depend significantly on unpredictable environmental factors.

Note that the accomplishment of required tasks is not simply a matter of generating percepts. Rather, what matters for accomplishing the (required/envisaged) tasks is the derivation of perceptual *guidance* which is needed for bodily actions, according to the understanding of active perception (see Section 1.2.1, page 3).

The derivation of such guidance, maintained by the processes of active perception, reacts to the unpredictable factors of the complex environment directly without using a model of world conditions. The stepwise evaluation of computed features and the determination of sensory-motor activities are generally embodied because they take account of three kinds of contingent factors: current environmental conditions, organisms' current positions and the already collected information. Because the explanation of route selection needs to take account of organisms' embodied response to unpredictable environmental factors, the derivation of adequate guidance maintained by active perception systems is by no means pre-determined. Hence, the explanation of active perception must be put in the context of emergence.

In the context of emergence, the adequate guidance of sensory-motor movements can straightforwardly be regarded as an outcome of *global* behaviour, beyond the direct effects of individual instructions which are stipulated in the algorithms of active perception implementations. Such a discussion seems to have moved to a point which itself does not serve as a ground of explanation, but instead as a target to be explained. This appears to be a retrograde step, because the discussion does not lead to a more familiar ground but conversely incurs *further* needs for explanation. This is partially correct. On the one hand, there does seem to be regression, because unpredictable factors and global behaviour is not specified in the algorithms of implementations. But on the other hand, there is progress in understanding the question, because the generation of the envisaged adequate guidance is put in an *appropriate* context of discussion - emergence - which itself has potential for substantive explanation, clearly distinguished from pre-determination.

6.2 Principles of Emergence

Emergence may have *common* principles applicable to all emergent phenomena, and *specific* principles pertaining to specific emergent subject matters. The origin of life is the archetype of emergence. In order to explain the origin of life four classical models have been entertained. These four models[1] might reveal certain common principles of emergence, which may help us to understand emergence in active perception. Yet, a caveat must be made. None of these four models provides *sufficient* conditions on the origin of life. Instead, each one provides at best salient *requirements* on attempts to circumscribe certain aspects of emergence which contribute to understanding the subject matter in question - the origin of life.

6.2.1 I. Rosen's model - The (M,R)-system

Rosen introduced his model - (M,R)-system - on the basis of the conception of metabolic networks, according to Morán *et al.* (1997). The production of M-units constitutes the baseline of life phenomena. Some of such units can be repaired, by R-units, while some others - at least one - cannot. Because of that 'non-re-establishable' element, organisms are mortal, a general feature[2] of life. The origin of life is explained in terms of the *maintenance* of those M-units by *reparation*, which presumes the existence of metabolic nets.

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[1] The exposition of three of the models is based on the introduction made by Morán *et al.* (1997). The exposition of Kauffman's autocatalytical network is mainly based on Kauffman (1995).

[2] It would be wrong to say that this is an *essence* of life, because permanent life would clearly be a case of life.

Re-appearance of Basic Patterns at a Higher Level and the Change There. As is easy to understand, the more such non-re-establishable M-units are produced the less would be the severity of the damage, when some of them are destroyed. Life emerges in a (M,R)-system, as characterised below. The (M,R)-system can be seen as a *catalytically-mediated metabolic net*, in which M-units are produced[3] under a recursive structure – certain reparation relations/patterns (between R-units and M-units) at one level can re-appear in the next higher level. In the course of life elaboration, substrate molecules at all levels remain the same but the re-appearing reparation patterns undergo change at the higher level.

Above is a minimum (M,R)-system, from which the recursive structures for reparation relations/patterns can *extend* (to more patterns) via new genomes. Specifically, new recursive structures can be generated in the genome by the generation of new machinery which produces the required catalysts of reparation. The details of generation are beyond the scope of the present thesis (for detailed discussions, see Morán *et al.* (1997), and Rosen's original texts – (1958, 1959, 1963, 1966, 1967)).

A Principle of Emergence – Modifying Basic Patterns Iteratively at a Higher Level. In the above discussions, what particularly concerns us is the extraction of a novel idea of emergence from Rosen's (M,R)-system. It would not be difficult to realise that a novel idea has been suggested – the *maintenance* of reparation within metabolic nets with *more* patterns of such maintenance (i.e. reparation). In particular, the aforementioned *recursive* structures of reparation may suggest an essential aspect of emergence – iteration with modification – especially for understanding the processes which lead to elaborate life phenomena. In the case of life origin, as a particular subject matter of emergence, what is modified is the catalytic[4] structures (in the metabolic nets) at a higher level. That is, the patterns of production and reparation can re-appear at a higher

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[3] Here, reparation can be regarded as a particular way of production.

[4] Reaction and diffusion are interpreted by Morán *et al.* (1997) as the two most fundamental types of biochemical interactions. Catalysis, as he states, can be seen as a special case of reaction.

level and then undergo change there. In other words, patterns of production and reparation *extend recursively* into the higher levels. This principle can be seen as a common requirement of emergent phenomena.

In contrast to above discussions, the reparation in the *metabolic* net may be a particular property pertaining to the subject matter concerned – (biological) life – as opposed to cognition. It must be noticed that the discussions of emergence in a different context, e.g. in active perception, would need to consider the particular properties pertaining to that new context.

In addition, Rosen's (M,R)-system draws a contrast between the baseline of emergent life and elaborate structures of life. The baseline of emergent life, from mere molecule structures, is the maintenance of reparation within a metabolic net; furthermore, the emergence of more elaborate life is understood as the generation of *more* relations/patterns of reparation in the *recursive* metabolic nets.

As a lesson for a general understanding of emergence, three principles/requirements can be extracted from Rosen's exposition of the most primordial characteristics of the subject matter– life:

1. **Baseline and Elaborate Patterns.** Emergent phenomena in a particular subject matter, be it life or active perception, need the distinction between a baseline and elaborate patterns of emergent phenomena.
2. **Iteration with Modification.** It is iteration with modification, such as the aforementioned recursive relations, that leads the process of emergence to elaborate emergent phenomena.
3. **Fundamental Structures of a Particular Subject matter.** Emergence must appear in a *particular* subject matter, in which the process of emergence must be grounded on the fundamental structures of that subject matter, such as the aforementioned metabolic nets and its two fundamental types of interactions – reactions and catalysis.

Of course, the interest of this thesis is not the origin of life. The discussion of the origin of life, yet, is not useless. In later discussions, these three requirements will be alternatively considered in the context of active perception, in order to help us to extract principles of task-level emergence.

6.2.2 II. Kauffman's model – The Autocatalytical Network

Kauffman (1993, 1995) explains the origin of life with a model called the *autocatalytic network/system*, which is a self-propelling loop maintained by self-produced catalysts (see figure 6.1), in contrast to the model of self-complementarity of nucleotide pairs suggested in Watson-Crick pairing rule.[5] Kauffman's idea is to draw attention to the more primordial role of *catalysts* in the origin of life, as opposed to template replication of genetic information.

As Kauffman suggests, the basic elements of a self-propelling loop are two simple monomers A and B, which are 'food' molecules. When energy is supplied from the outside, these two simple monomers compose dimers AB and BA, which serve as two catalysts for producing BA and AB respectively. This network maintains iterative production of *catalysts* (AB and BA) which are needed for the production of food molecules As and Bs – this loop *sustains itself*. Hence, this network is *autocatalytic*.

Considering the three requirements derived from Rosen's (M,R)-system, Kauffman's model focuses on baseline phenomena of life, without aiming to account for elaborate forms of life. The iteration, as a consequence, is not accompanied with modification. To address the particular aspect of life origin which Kauffman considers most primordial, this model particularly concerns the availability of catalysts, which is fundamentally important for biochemical production.

Kauffman's model suggests a novel approach to emergence: the baseline of

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[5] The Watson-Crick pairing rule, briefly, suggests an intuitive model of gene maintenance, in which the parts of one helix of the gene that have undergone mutational degradation can resume themselves by the *template replication* of same information from the nucleotide pairs of the other helix of the same gene. Given that there are only two nucleotide pairs in genes, A-T and C-G (i.e. adenine-thymine and cytosin-guanine), the lost nucleotides in a section position of the helix can be recovered by complimented replication of the other nucleotide of its pair, say T. The lost nucleotide must be A, hence an A is replicated in the position of lost information. For details, see Kauffman (1995) pp. 32-43.

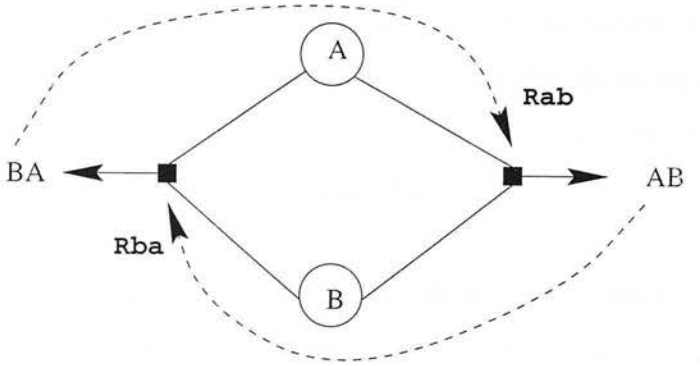

Figure 6.1: **A Simple Illustration of Kauffman's Model of Autocatalytic Network.** Two types of dimer are produced in this network. One type of dimer – AB – catalyses the reaction R_{ba} that joins As and Bs to produce BA. Similarly, the other type of dimer – BA – catalyses the reaction R_{ab} that joins As and Bs to produce AB. Because of this autocatalytic network – the network that maintains iterative production of catalysts (AB and BA) which are needed for the production of food molecules As and Bs – this loop sustains itself. Re-drawn from Kauffman (1995), p. 49, Figure 3.1.

life phenomena as the production of needed biochemical materials (catalysts) for the *self-sustenance* of biochemical organisations/systems[6], while such organisations/systems are simply exemplified by the autocatalytic network. The self-sustenance considered by Kauffman can be understood as a *minimally stable and continuing collective phenomenon* (i.e. autocatalytic network) composed of basic components (i.e. monomers). The maintenance of such a network can be regarded as the baseline, i.e. origin in the simplest case, of emergence.

Recall that Rosen's (M,R)-system presumes the existence of metabolic nets, which needs to be explained in the first place. Because the self-sustenance[7] of biochemical organisations/systems can be seen as a central characteristic of life origin, Kauffman's model serves as an exposition of a most primordial characteristic of life, as distinct from other characteristics (such as template replication at

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[6] According to Varela and Maturana (1973), an organism must have clear identification of biochemical *structures*, while this requirement is relaxed (i.e. need not be strictly followed) in considering its functional organisation. In the present discussions, the identification of particular biological structures is not important. Hence, there is not much difference between organisations and systems, nor is there a significant difference between network and system.

[7] It is important not to confuse self-sustenance with the self-supplying of energy, which is impossible for living organisms. The energy for the autocatalytic network, as previously mentioned, must be supplied from outside the organism.

gene level). Like Rosen's idea of emergence in his (M,R)-system, a requirement of task-level emergence is to maintain a *most primordial* characteristic of active perception. Hence, the discussion so far derives a requirement on emergence, additional to the previous three requirements:

> 4. **The Baseline of Emergent Phenomena as the Self-sustenance of the basic organisations/systems of the subject matter.** The *baseline* phenomenon of emergence, as suggested in Kauffman's idea of autocatalytic network, is the maintenance of a minimally stable and continuing collective phenomenon (e.g. autocatalytic network) of basic structures (e.g. monomers).

This requirement on emergence will contribute to explaining emergence in the context of active perception (see Section 6.2).

6.2.3 III. Eigen's Model of Hypercycle

Eigen (1971) proposes a model of evolving RNA strands, as described by Morán *et al.* (1997). Single RNA strands themselves are incapable of evolution, because they are *per se* too simple. The single autocatalytic cycles of different RNA strands, on the basis of the aforementioned Watson-Crick pairing rule (i.e. the maintenance of template replication with A-T pair and C-G pair), will end up with the production of single enzymes. At this level, no further organisations are seen.

The Generation of a Hypercycle. Evolving autocatalytic systems need the connections between the above autocatalytic cycles, connections that lead to a *global* cycle. Specifically, a connection is maintained in the global cycle when the enzymes produced in one autocatalytic cycle serve to catalyse the template replication of a neighbouring autocatalytic cycle. When such connections of autocatalytic cycle *themselves* constitute a cycle, a *hypercycle* is generated.

Stability of a Hypercycle. A hypercycle can be more stable than its component autocatalytic cycles. Once the above connections are maintained across autocatalytic cycles, the functional properties of this hypercycle are preserved. This still happens, even if *some* of the component autocatalytic cycles undergo fatal mutation. Mutation may give rise to a catastrophe in the process of self-reproduction. However, if *some other* reliable components still push forward the production of enzymes to catalyse neighbouring autocatalytic cycles, the functional properties of the whole hypercycle are preserved. As a consequence, whole hypercycle is robust, and more reliable than its component autocatalytic cycles.

Illustrating a Hypercycle – A Cycle at a Higher Level, Not a Moving Component Cycle. A figure may help to understand the generation of a hypercycle on grounds of component autocatalytic cycles. When a certain autocatalytic cycle AC_i produces the enzyme E_{i+1} needed for pushing forward a neighbouring autocatalytic cycle AC_{i+1} and AC_{i+1} is actually so catalysed, a connection is formed between AC_i and AC_{i+1}. When AC_n is connected, in this way, back to AC_1, a hypercycle is formed. Notice that a hypercycle presumes that all its component autocatalytic cycles continue sustaining.

A Principle of Emergence – A Global Autocatalytic *Cycle* of Component Autocatalytic Cycles. A principle of emergence can be extracted from Eigen's hypercycle model of life origin, to support the discussions of emergence in the present thesis. Eigen's hypercycle model of life origin, as we have seen, apparently concerns the elaboration of life phenomena, in contrast to Kauffman's baseline model of life origin. However, the elaboration of life phenomena discussed in Eigen's model, unlike that in Rosen's (M,R)-system, is not based on recursive structures/patterns of repair. Rather, it (the elaborate life) consists of the catalytic connections between component autocatalytic cycles, if only those connections (between component autocatalytic cycles) *themselves* constitute a cycle.

This newly generated form of life – a hypercycle of component autocatalytic

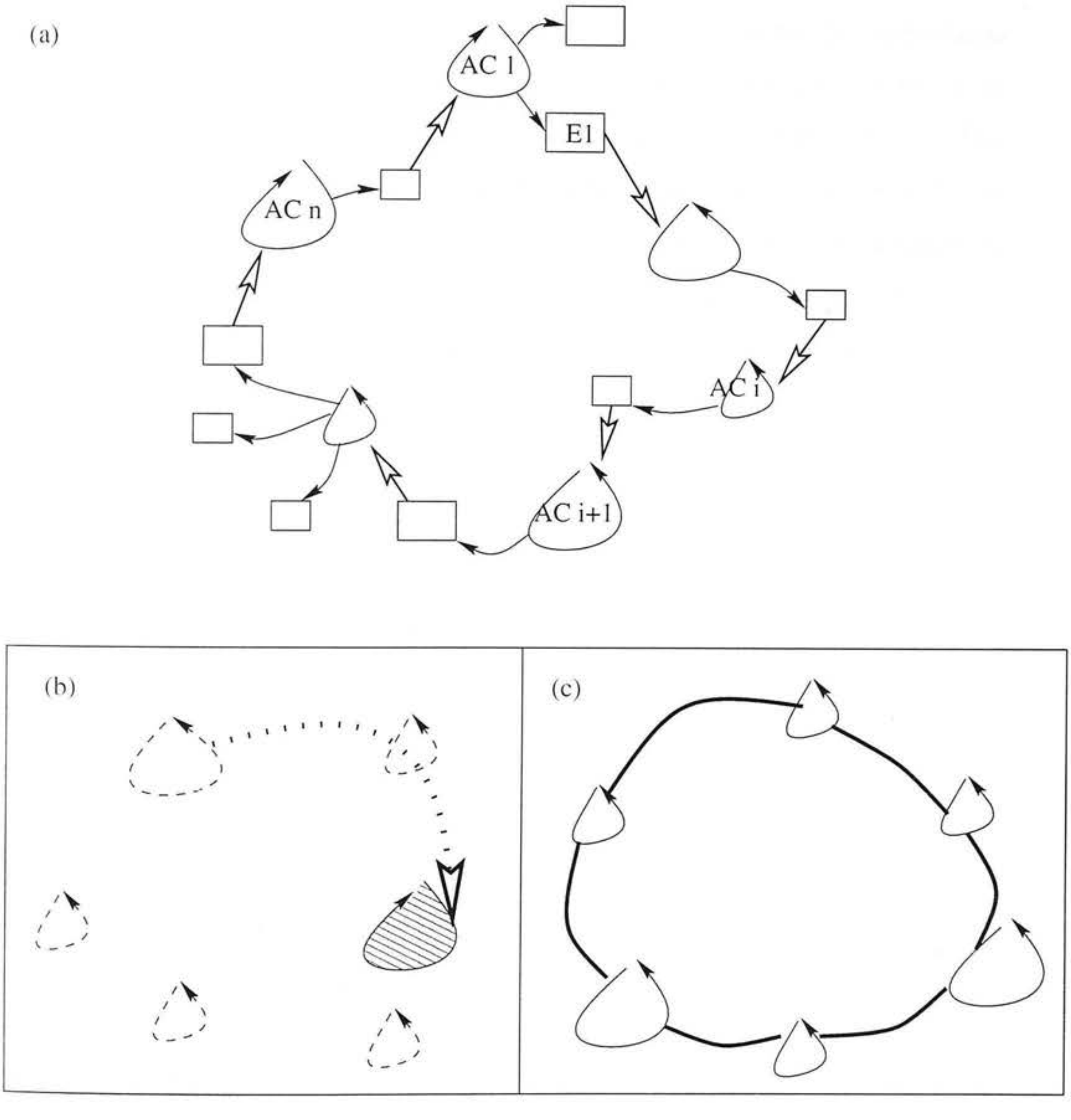

Figure 6.2: **A Hypercycle is Itself a Cycle, but takes place at a Higher Level.** A hypercycle consists of the catalysts connecting a series of autocatalytic cycles. Figure (a) shows that the enzymes produced in one autocatalytic cycle catalyse a neighbouring autocatalytic cycle. When such connections of autocatalytic cycles *themselves* constitute a cycle, i.e. the last cycle produces the enzymes needed for the maintenance of the beginning cycle, a *hypercycle* is generated. Notice that catalysed cycles will not stop sustaining when they produce certain enzymes for the next component cycle in this hypercycle. All component autocatalytic cycles persist when the hypercycle is capable of sustaining itself. While figure (b) is tantamount to a seemingly moving 'point' across component cycles, figure (c) illustrates a real cycle. Figure (b) is a wrong model of hypercycle, whereas figure (c) is a correct one. Among these three figures, (a) is re-drawn (with an interpretation) from Morán *et al.* (1997), Figure 2, p. 258.

cycles – take place at a global level. A cycle, by nature, can sustain itself, thus fulfilling the baseline requirement of life origin. Along with the connections in a hypercycle, the functionality of a previous component autocatalytic cycle will reinforce the functionality of a later component autocatalytic cycle. The functionality of the hypercycle accordingly differs from that of any component autocatalytic cycle, given that the self-sustenance of the hypercycle is based on catalytic connections across various RNA strands while the maintenance of each component autocatalytic cycle consists in the template replication within the same RNA strand.

Note that the notion of hypercycle falls into the previous categories of 'iteration and modification'. A cycle itself iterates the catalytic connections between its components. The modification takes place at the jump of levels from components (local) to the global level. A principle of emergence, thus, can be extracted:

> **5. The Hypercycle of Component Cycles.** A hypercycle emerges whenever the connections between its component cycles themselves constitute a cycle (of course at a different operational level), where a cycle is understood as an organisation/system which somehow sustains itself. In other words, self-sustenance at an operationally global level leads to emergence.

6.2.4 IV. Maturana and Varela's Autopoietic Model of Life Origin

Apart from the previous three models, the subject matter of life origin is also explained in the model of autopoiesis[8] proposed by Maturana and Varela (in Varela *et al.* (1974)). The model of autopoiesis, as described by Morán *et al.* (1997), consists in two requirements on a self-maintaining network/system at different spatial scales – continuing reproduction of *components* and the maintenance of the *network/system itself* as a concrete unity in real space and time. To put it another way, a living system needs to self-maintain (i) the availability of all its

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[8] Autopoiesis is Greek word, which roughly means self-production (see Varela *et al.* (1974)).

components and (more essentially) (ii) the organisation of such components into a unity distinguishable in real space and time from its surroundings.

The model can be applied to different subject areas, such as biology, cognitive science, and mathematical logic, if only those two requirements are fulfilled. As an archetypal example, a biological system must evolve (specifically, via the polymerization[9] of substrates by catalysts) a spatially closed membrane to distinguish it from *its* surroundings.

Processes of Interaction Within the Autopoietic Unity. Not discussed in Morán *et al.* (1997), but intrinsic to the notion of autopoiesis, are the processes that *realise* the operationally (but not necessarily spatially) separable unity from the background. Those processes constitute a network of *interactions* between components, which are exemplified by the generation of a (spatially closed) membrane. The membrane has a clear spatial boundary, but the processes of interaction need not. Why can there be constant invariant organisation (i.e. the autopoietic unity) out of such interactions?

The membrane *per se* does not explain the operationally separable *unity* in question. As an example given by Varela *et al.* (1974), a crystal is a system with fixed *spatial* relations, but is not an autopoietic unity, because there are no processes of interaction that establish the autopoietic unity. As explicitly characterised in the six criteria of autopoietic unity, boundaries themselves do not characterise an autopoietic unity. What is essential to the notion of autopoietic unity is not the boundaries *per se*, but the 'preferential neighbourhood relations and interactions between [components]' which realise the boundaries. They realise boundaries hence they are more primordially important than the boundaries *per se*. Even if the boundaries break, the autopoietic unity can be re-gained on the basis of the above neighbourhood relations and interactions, as demonstrated in the second global behaviour of the computer simulation described below.

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[9] Polymerization is the process leading to polymers. Polymers are compound large molecules made up of linked monomers, simple repeated units of the same types, such as proteins and nucleic acids.

To see boundaries from another angle, the autopoietic unity of a cell may reveal the difference between membrane *per se* and the processes that lead to the boundaries of autopoietic unity. Note that membranes are not themselves boundaries, because those boundaries are understood on account of their processes/operations, which go beyond spatial relations. Hence, the autopoietic unity of a cell is not grounded on its membrane *per se*, but on the metabolic closure maintained by the interacting processes between the within-membrane cellular substrates.

A Simple Example of Living System by a Computer Simulation. In Varela *et al.* (1974) the above notion is exemplified by a computer simulation with three instructions.

[1] Composition (linking): $\star + 2\bigcirc \rightarrow \star + \oplus$

[2] Concatenation (bonding): $\underbrace{\oplus - \oplus - ... - \oplus}_{n} + \oplus \rightarrow \underbrace{\oplus - \oplus - ... - \oplus}_{n+1}$

$n = 1, 2, 3, ...$

[3] Disintegration: $\oplus \rightarrow 2\bigcirc$

The first instruction[10] concerns composition, stating that two substrates supported by a catalyst lead to a *linked* substrate, with that catalyst still being there. The second instruction states that n *bonded*[11] substrates interacting with another substrate lead to $n+1$ bonded substrates. Note that this is a *recursive* rule of bond generation. It means that the emergence of longer links is grounded on recursive processes. The third instruction concerns the disintegration of bonded substrates, which may be caused by collision between substrates or the natural decay of bonded substrates.

The simulation system begins with a two-dimensional quadratic grid which consists of substrates with one catalyst in between. With these three instructions,

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[10] The symbols are somewhat different from those in Varela *et al.* (1974), but this does not affect the understanding of this computer simulation.

[11] Biochemical links and bonds need not be strictly realised by spatially neighbouring links, because lots of messengers can travel across limited space and interact with remote molecules.

the result of simulation demonstrates two salient global behaviours. Firstly, a chain of bonded linked-substrates ⊕ eventually forms an enclosure for the catalyst, which is tantamount to the spontaneous generation of an autopoietic unity. Secondly, the chain of bonded linked-substrates ⊕ sometimes breaks, while ongoing production manifests compensation of bonds in the broken area, which re-establishes the autopoietic unity.

A comment about this simulation is made by Varela *et al.* (1974), that the autopoietic unity is neither represented not embodied in the scheme of those three instructions *per se*, nor is it identical to its components. This is seen in their statement: 'in general no organisation is represented or embodied in the properties that realize it (p. 191)'. In other words, Varela *et al.* (1974) see the generation of autopoietic unity as an emergent phenomenon (i.e. a global behaviour), which is not *tantamount to* its components and the interacting activities, in the sense of non-transparently reducible[12] to the mere combination of those components. This attitude echoes the original motivation in emphasising the essential importance of autopoictic unity: *reproduction* of components does not explain the underlying unity of living organisms, as proclaimed by Varela *et al.* (1974) in the introduction to their paper. In addition, they indicate that the

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[12] A network/system is non-transparently reducible to the mere combination of components when, and only when, the combination of components presents phenomena beyond *transparent reduction.* The notion of transparent reduction means the explanation of a combination completely on grounds of its components, which may take the form of computational processes specified by the instructions of algorithms. For example, most learning in the PDP is not transparently reducible, in that the learnt functionality cannot be fully described in terms of the behaviour of particular nodes, the weights of particular connections, and the single changes controlled by the instructions of algorithms. Despite the difference between PDP and *physical* systems (as opposed to chemical systems), the notion of transparent reduction is similar to another notion – micro-reduction (Oppenheim and Putnam 1958) – that the behaviour of a physical system can be fully explained on the basis of the behaviours of its components, the basic physical entities such as particles, velocity and mass. Common to these two notions is a general principle that the whole can be fully explained on the basis of its components. Contrasted to the notion of transparent reduction is a perspective which maintains a looser sense of reduction: the behaviour of *any* system (even a neural network with non-linear connections) is *in principle* (necessarily) understandable on the basis of the behaviours of its components. If only the understanding of the behaviour of the whole system takes account, at bottom, of the behaviours of its components, the whole system can be seen as reducible in terms of its components. Accordingly, even a non-transparently reducible system must still be *in principle* reducible to its components. Thus, the notions of *transparent* reduction, on the one hand, and reducibility *in principle*, on the other, can be seen as subject to different emphasises of explanation. The former emphasises on the generation of behaviours which are not directly describable in terms of behaviours of *single* components, by contrast, the latter on whether *additional components* or descriptions of them are needed to explain the whole system.

same components of an autopoietic unity can be allopoietic, i.e. leading to a *different* product from the original organism. It is, rather, the network of interacting processes (of the components) that leads to that underlying unity.

It is worth noting that the generation of such a network can be seen as emergence, despite the three *language-like* instructions. This shows that the instructions of an emergent system may well be language-like rules. This simulation of emergence exemplifies our previous definition of emergence as non-pre-determination, where there is nothing mentioned about language-like rules (see Section 2.6, page 64). What matters for emergence (i.e. non-pre-determination) is that interacting processes do not begin with pre-categorised data but can be directly affected by factors in the environment. This is shown in the above simulation, where the components in the environment (i.e. the two-dimensional quadratic grid) interact directly without being mediated by (the trigger of) pre-categorised data.

A Principle of Emergence in connection to Autopoiesis. An autopoietic unity differs from a hypercycle, although both of them are global behaviours. A hypercycle is not an autopoietic unity, for two reasons. Firstly, a hypercycle presumes many component cycles, while an autopoietic unity need not. To see this from another angle, a hypercycle must have component cycles, while an autopoietic unity need not have further component autopoietic unities. Secondly, autopoiesis is a process of producing component biochemical structures. Yet, a hypercycle *presumes* its component cycles without *producing* them. A single component cycle must have certain *fundamental biochemical structures* before it is pushed forward by certain *catalysts* issued from another component cycle. Such catalysts do not amount to a single component cycle. The hypercycle is a global phenomenon in which an existing component cycle serves to facilitate the continuity of another *existing* component cycle.

Autopoiesis differs from Kauffman's autocatalytic cycle, although they both concern self-sustenance (of a living system). Autopoiesis concerns the unity of *all* living organisms, while the autocatalytic cycle has a specific focus on the self-sustenance of a *minimal* network. Autopoiesis does not simply apply to a minimum requirement of a living system, but also to the recovery or even *re*production[13] of itself. It even applies to a hypercycle, given that a hypercycle needs an autopoietic unity.

Accordingly, the notion of an autocatalytic cycle is more *sharply* focused than the notion of autopoiesis, regarding the kinds of living systems it applies to. This is probably because Kauffman's notion (autocatalytic cycle) was published much later, by about two decades. Kauffman does say something beyond the notion of autopoietic unity, given that Maturana and Varela do not specifically address the *minimum* network of life and explain it in terms of the auto*catalytic* cycle (as opposed to other mechanisms, such as the aforementioned gene maintenance according to the Watson-Crick pairing rule). However, Kauffman's notion has its sharper focus at the expense of a narrower coverage in the application to living systems.

The processes leading to autopoietic unity are basically iterative local transformations of substrates in the environment. Whenever such transformations (as a global behaviour) lead to an *operational closure*[14], an autopoietic unity emerges. The emergence of an autopoietic unity, briefly, can be characterised as the processes of an organism that lead to the re-production of itself, which is evident in the presence of their operational closure. The emphasis is not on self-*sustenance*, but on the *re-production* of components with operational closure, i.e. iterative generation from parts to whole.

> **6. The Emergence of Identical Systems.** For a living system, the emergence of another operationally identical system can be grounded on three stages of emergence – re-producing its components, iterative transformations of such components, and operational closure of such transformations.

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[13] The above computer simulation demonstrates the recovery of an autopoietic unity. Self-reproduction requires autopoiesis. As it is written: 'self-reproduction must take place during autopoiesis' (p. 101).

[14] An autopoietic unity can be characterised in terms of operational closure. It is actually so characterised in Varela *et al.* (1991), p. 157.

Above, six common principles of emergence are derived from explaining the origin of life, which are extracted from four models of life origin – I. Rosen's (M,R)-system, II. Kauffman's autocatalytic cycle, III. Eigen's hypercycle, and IV. Maturana and Varela's autopoiesis. These six principles will be applied to another subject area – active perception – in order to derive the basic principles for explaining its emergence. As a reminder, such principles do not complete the understanding of emergence, but serve as common *requirements* on emergence, although they are derived from a specific subject area (the origin of life).

6.3 Requirements on Task-level Emergence.

This section concerns requirements on task-level emergence. Before we set off to build principles of task-level emergence, let us briefly organise the relations between the previous four models of life origin and the various stages of task-level emergence.

6.3.1 An Outline of Principle Extraction.

To see the aforementioned relations clearly, they are arranged in the form of a table:

This table provides a general outline of the various stages of task-level emergence, which correspond to different principles extracted from the previously discussed four models of life origin.

Corresponding to Maturana and Varela's notion of autopoietic unity is the core characteristic of all active perception systems: at a given *step* of computation, a system should maintain both the *comparison* of achieved information and the needed information for accomplishing the required *task*, on the one hand, and the actual *derivation* of information to guide the next step of computation (which may begins with sensory-motor movement), on the other. If an active perception system is capable of maintaining these two jobs (comparison and derivation) *in each single step*, this system would also be capable of accomplishing the required

Models	Characteristics in the origin of life	Characteristics in active perception
Rosen's (M,R) system	Iterative modifications, a lift from baseline patterns toward elaborate patterns	Stepwise computation, a lift from small systems toward a combinatory system
Maturara & Varela's autopietic unity	Operational closure of a system	Comparison between collected information and the needed information
Kauffman's autocatalytic network	Self-sustenance of a minimum living system	Stepwise computation in a single system, internal cohesion in this system
Eigen's hypercycle	A cycle connected by component cycles	Stepwise computation in a combinatory system, with sub-systems mutually support

Figure 6.3: **Comparison of Four Models of Life Origin and Their Respective Relations to Different Emergent Phenomena in Active Perception.** From four models of life origin we can extract principles of task-level emergence to explain various stages of task-level emergence, from single simple systems to elaborate systems.

task (by deriving certain perceptual guidance which fulfils that task). Hence, it makes no difference whether we interpret autopoietic unity as the comparison *in a single step* of computation or interpret it as the comparison leading to the actual accomplishment of a required task *within a single system.*

Kauffman's notion of autocatalytic cycles suggests the baseline of task-level emergence, the *stepwise* computation maintained in a simple single active perception system, such as the attentive control of saccades.

Rosen's (M,R)-system indicates a difference between baseline and elaborate patterns of emergence, and thereby suggests a distinction between a simple system and a combinatory system. The latter system, as exemplified by Dickmanns' car, consists of many sub-systems which are organised in (parallel or heterarchical) relational structures.

In this table, notice that the processes of internal cohesion are located in two positions. Such an allocation indicates that emergent processes take place at two levels: lower and higher. Those at the lower level concern the task-level emergence of a *single* system, such as attentive control of saccades or Adept; by contrast, those processes at the higher level concern the task-level emergence of a large system, such as Dickmanns' car, gaze control, tracking capacity/capability, or even the combination of all these systems. The processes that maintain internal cohesion at the lower level lead to the computation of information *within* a single small system. The computation at this level corresponds to Rosen's baseline patterns of emergence phenomena and Kauffman's notion of autocatalytic cycles. In contrast, those maintaining internal cohesion at the higher level lead to computation *across* systems (such as gaze control, tracking, or Dickmanns' car), which corresponds to both Rosen's conception of elaborate patterns of emergence and Eigen's notion of hypercycle.

6.3.2 Fundamental Structures of Active Perception

Below are detailed discussions that extract principles of emergence from models of life origin. Discussions begin with the six requirements on emergence derived from the four models of life origin (see Section 6.2 page 212). The emphasis, however, is on the consideration of them in the context of our subject matter – active perception. Although those six requirements are common principles of emergence, they really arose in a context different from ours. As a consequence, the first step in the following discussions is to isolate the fundamental structures of active perception, as opposed to the metabolic nets and its two (among others) fundamental types of interactions – reactions and catalysis. This is explicitly required in the third principle derived from the previous discussions on Rosen's (M,R)-system.

As discussed in previous chapters, the task of active perception is to provide guidance of bodily actions. More precisely, a requirement can be derived:

> **Principle 1. The Context Of Task-level Emergence – Computation for Deriving Guidance of Sensory-motor Movements and Bodily Actions.** The fundamental structures of active perception are the iterative *computational processes* of perceptual inputs based on the most fundamental type of interaction – process selection – with the effect of deriving guidance for sensory-motor movements, and such iterative computation eventually leads to the fulfilment of the required *tasks* – providing guidance for bodily actions.

This principle indicates two salient differences between task-level emergence and the origin of life – (1) computation that leads to (2) the accomplishment of tasks. Regarding point (1), systems of active perception do not maintain biochemical processes, but maintain computation over information. Regarding point (2), the aim of active perception systems is not self-sustenance but the accomplishment of the required tasks.

Bringing these two points together, the computation for accomplishing tasks, in a nutshell, needs the *comparison* between three sources of information – (a) the previously *achieved information* initiated by sensors, (b) the *tasks* imposed from outside the active perception systems (e.g. from intentions) which can be fulfilled by active perception systems with perceptual guidance (in support of bodily actions), (c) the needed information for the next step of computation indicated by these systems in the light of accomplishing the required tasks. The *derivation* of point (c) stands as the leading characteristic of all active perception systems.

Note that the computation of an active perception system may be interrupted but such a system should basically be capable of carrying out the whole cycle of computation leading to the derivation of the perceptual guidance that fulfils the required tasks. For example, tracking a moving ball may be interrupted/distracted by a sudden sound. However, in the circumstances where no interruption arise, a tracking system should be capable of providing perceptual guidance for catching that ball.

After considering the first principle, discussions of task-level emergence should address the baseline requirement of active perception, i.e. what constitutes a *minimum* system of active perception.

Kauffman's model of autocatalytic network (see Section 6.2.2, page 215) suggests a requirement for understanding the task-level emergence of active perception.

6.3.3 The Baseline of Emergent Phenomena as the Stable and Continuing Processing of Single Systems of Active Perception

Considering the subject matter of active perception, the baseline phenomenon of emergence (which is exemplified in Kauffman's model by the autocatalytic network/system for the maintenance of biochemical organisations) would be the *self-sustenance* of the simplest organisations/systems of active perception: that is, the (minimal stable) continuation of those systems' functionality simply by re-using their own outputs as inputs. Despite this general feature, there seems to be no single answer as to what exactly a baseline phenomenon of task-level emergence is like. The baseline phenomenon of active perception seems to be *multiply realised*, as evident in many systems of active perception each of which provides a particular characteristic of active perception. That is, every implementation of single phenomenon (of active perception) can be seen as a baseline phenomenon of emergence.

For example, a simple model for the attentive control of saccades explains the self-sustenance of selection over saccades, specifically as follows:

> **Principle 2.1. The Baseline Emergence of Attentive Control of Saccades.** The baseline emergence of attentive control of saccades can be explained as the stable and continuing collective phenomenon of selection over basic components (compared with monomers in Kauffman's models) of visual perception – the roughly attended features gathered from the visual inputs.

As another example, Snake (as a general algorithm) captures the phenomenon of internal configuration of component visual images, by smoothly linking together the images of line, angle, curve, etc., under the influences of different degrees of forces imposed on such component images.[15] Within Snake self-sustenance must be achieved. That is, the system of Snake must run stably and continually. While the self-sustenance in the context of life origin is explained by the notion of autocatalytic cycle – a characteristic of life origin – the self-sustenance here is explained as follows:

> **Principle 2.2. The Baseline Emergence of Tracking by Snake.** Snake provides a baseline understanding of tracking (apart from the Kalman filter), under the notion of smoothly linking together component images under the influences of the different (degrees of) forces imposed on such component images.

There remain more examples, such as the Kalman filter, Adept, and pursuit.

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[15] What component images are implemented depends on what basic components are actually in-built in the particular Snake.

In fact, insofar as we have surveyed, the implementations of active perception almost all are dedicated to single simple phenomena (of active perception), except for Dickmanns' car. The implementation of each single phenomenon would provide a particular characteristic of the emergence in question – task-level emergence.

6.3.4 The Emergence of Elaborate Systems – Iterative Modification of a Combinatory System at a Higher Level

Having discussed the baseline phenomena of emergence, we need to turn to the *elaborate* phenomena of emergence. As suggested in previous discussions of Rosen's (M,R)-system (see Section 6.2.1, page 212), emergent systems may undergo elaboration, in which the basic patterns undergo change/modification iteratively at a higher level. Notice that in the context of Rosen's (M,R)-system the notion of *level* refers to recursive biochemical structures; yet, in the context of active perception, the notion of level may not mean that.

In the task-level emergence of active perception, the conception of iteration – i.e. iterative *levels*[16] – may refer to the iterative *cycles* of computation at run-time, in which the basic structure is not biochemical connection but process selection, such as the computation of *next* target position of saccadic movement. In the next cycle of computation, the process selection is maintained by comparing (the weights of the attended features, in the case of attentive control of saccades) the previously achieved features and the needed features *for* the required tasks.

Consider the computation for the *next cycle* in Dickmanns' car, gaze control, and tracking capacity/capability, which may be conceived as *combinatory systems*. When the computational process of a sub-system/small system (such as the attentive control of saccades, as a component sub-system of gaze control) proceeds to a next level/cycle/step, the computation may *need* to take account

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[16] Obviously, one must not literally identify the term 'level' here with the term 'level' in 'task-level emergence'. In fact, the term 'level' has a variety of references, but one will be singled out according to its context. At least three kinds of level are distinguished in Churchland and Sejnowski (1992) – level of organisation, level of spatial scale, level as processing stage.

of influences from other sub-systems (such as pursuit system). Information from other sub-systems is needed, because gaze control must make corrections over certain errors resulting from the computational time or otherwise (see Section 3.4.5, page 104). The gaze control consequently becomes elaborate (than simply the attentive control of saccades). If we regard the attentive control of saccades as a sub-system of guidance at a lower level, then the influences can be seen as taking place at a higher level of gaze control. At a higher level the gaze control can be seen as undergoing *iterative modification.* Thus, a principle can be framed as to the task-level emergence of *elaborate* systems:

> **Principle 3. System Elaboration Through Iterative Modification at a Higher Level.** An active perception system can have its computation elaborated when the computation proceeds to a next step. A next step can be seen as a higher level of computation. Through iterative computation at a higher level, elaboration takes place, in the sense that the computation proceeds nearer and nearer toward the required task.

The application of Rosen's notion of iterative modification at a *higher* level is not limited to gaze control. It can also be applied to Dickmanns' car and tracking capacity/capability, and any *combinatory* system. All of them consist of iterative processes with later steps of computation enhanced by other sub-systems in the same combinatory system. Eventually the computation of a combinatory system proceeds nearer and nearer to the required tasks.

6.3.5 The Autopoietic Unity of an Active Perception System.

The explanation of task-level emergence can be further supported by another model of life origin: Maturana and Varela's notion of autopoietic unity (see Section 6.2.4, page 220). The above discussions are inspired by Rosen's notion of re-appearance and change at a higher level. However, the basic conception of a computational cycle *as such* was presumed and needs further explanation.

In this regard, a explanation can be inspired by Maturana and Varela's notion of autopoietic unity. Specifically, the notion of a computational cycle, and the notion of generating a new cycle of computation need explanations regarding their autopoietic unity.

In the context of computational cycles, the notion of autopoietic unity can be understood as an operationally identical system, with three stages of emergence – the generation of component perceptual features or routes of sensory-motor movements, iterative transformations of them, and, most important, the operational *closure* of such transformations. In the context of active perception, the notion of operational closure can be interpreted as the *completion* of computational processes under the same mechanisms *before the re-initiation* of continuing computational processes under those mechanisms.

With this interpretation, understanding a cycle of attentive control of saccades is focused on the *completion* of computational processes under the mechanisms of the above attentive control. The completion of certain computational processes *must* happen before the re-initiation of another cycle of those processes. The aforementioned three models of emergence have different emphases. Rosen's principles of emergence emphasise the re-appearance and change at a higher level, and Kauffman's principle emphasises the self-sustenance (stable and continuing self-maintenance) of an elementary system. By contrast, Maturana and Varela's principles of emergence focus on the completion of the generational processes associated with a single system. Accordingly, the *iterative* computation of active perception not only needs to address *novel* perceptual features and *useful* internal transformations but also is required to complete the computation in each cycle.

As it happens, the completion of a single cycle is insured by the comparison of the already gained computational achievements with the information still needed for the required tasks. Neither novel features nor useful transformations suffice to explain task-level emergence without considering that *comparison*. The completion of a cycle must be ensured by that comparison before the initiation of the next cycle. Thus, the task-level emergence of active perception does not entirely consist in the collection of novel features and the derivation of useful transformations, but also in the computational activity that *insures* the previous outcome will really contribute to the required tasks. Without insuring this contribution, the computational processes, however subtle they are, cannot qualify as a cycle of active perception.

Like the closure of operational processes which is claimed to be essential to a living system in Maturana and Varela's notion of emergence, the concern of accomplishing the required tasks (as evident in the aforementioned activity of comparison) is what is essential to active perception, rather than the computational processes that serve to make available and transform perceptual information. That is, the processes of active perception are essentially the computational processes that *insure* the contribution of collected information to the *need* for an externally required task. A principle of task-level emergence can consequently be derived:

> **Principle 4. The Autopoietic Unity of an Active Perception System – Insuring the Contribution to Tasks.** What is essential to systems of active perception is not the computational processes for information collection and their internal transformations, but the processes for insuring their contribution to the required tasks.

Task-level emergence, as a consequence, is intrinsically grounded on the computation concerning the contribution of information collection to the externally imposed tasks.

An Inherent Pragmatist Stance in Active Perception. The above discussions about the contribution of collected information to tasks imply that the *functionality* of autonomous systems ends up with the support of their *use*: deriving the needed information in support of the externally imposed tasks. This signifies a philosophical interpretation of active perception, that the systems of active perception are ultimately *pragmatist* systems, in the sense that what perceptual information is to be collected at the next step of sensory-motor movement depends on the *contribution (consequences)* of the would-be collected information to the currently required task. In other words, the computation of what an optimal next step of sensory-motor movement would be does not depend on properties of that would-be step *per se*, but instead on its consequences/contributions (to the currently required task). As a result, the content of a perceptual scene (i.e. the perceptual understanding) needs to be organised on the basis of its consequences – specifically, the contributions of its ingredients to the required task. It is, therefore, not illegitimate to say that task-level emergence essentially presumes certain pragmatist features.

Autopoietic Unity as the Autonomy of an Autonomous System. The autopoietic unity of a living system is regarded by Maturana and Varela as its autonomy. Similarly, the computational processes that insure the contribution of collected information to the need of an externally required task can be seen as the autonomy of an active perception system. Somewhat surprisingly, the autonomy of an autonomous system has a pragmatist basis. This point will be continued in later discussions in the present thesis.

6.3.6 Understanding of Task-level Emergence in Terms of Eigen's Notion of Hypercycle.

The notion of single cycles in the context of active perception having been discussed, we can proceed to discuss Eigen's notion of hypercycle, which is a global phenomenon on the basis of component cycles. The understanding of task-level emergence would be incomplete, without understanding the global phenomenon of components' cycles, which refers to the global behaviour of component single cycles in active perception systems, as exemplified by the accomplishment of any active perception system, including a relatively complicated case – Dickmanns' car.

In the context of active perception, a hypercycle can be identified with a combinatory system plus a requirement: the system carries out a series of computational processes (leading to the accomplishment of a required task) on the basis of the *mutual support* provided by the computational results of *sub*-systems.

The Global Behaviour Manifested in a Hypercycle. A hypercycle refers to the series of computational processes/steps/cycles *leading to the accomplishment of a single task*. The importance of a hypercycle beyond its component cycles can be seen from the mutual connections of those component cycles. In other words, no task of a combinatory system can be accomplished without the mutual support of the sub-systems. The completion of a task is a *global* phenomenon of component cycles, which may pertain to different sub-systems. This is because the completion of a task results from the mutual support between those sub-systems, which is not *transparently reducible* to the *mere* combination of the cycles provided by all sub-systems (see Section 12, page 223). The global behaviour of task accomplishment, as suggested in the notion of hypercycle, consists of the *connections* of computational processes leading to the accomplishment of the required tasks. Furthermore, the end of the hypercycle is also a beginning for another hypercycle; likewise, the accomplishment of a single task constitutes the beginning of another task.

A note should make to clarify the nature of a hypercycle. A hypercycle is a series of computational processes in a combinatory system, as above defined. Two confusions should be avoided. First, a combinatory system is not itself tantamount to a hypercycle, but can be conceived of as its *bearer*. A hypercycle, accordingly, corresponds to a single task, which is supported by the non-transparently reducible combination of all the sub-systems. Second, when the computational processes are running, in the sense that various sub-systems 'take turns' to control the combinatory system, the sub-systems may continue their respective computation, without stopping and waiting for their 'turn'. To use an analogy, a hypercycle is itself a cycle, not a moving point (see Section 6.2, page 219).

Hypercycle and Activeness. Discussions of task-level emergence must explain *how* a hypercycle emerges from its component cycles. It is not hard to realise that the *how* question addressed here is exactly the question of explaining *activeness* previously discussed. The answer, unlike previous discussions on grounds of models of life origin, is not derivable directly from the notion of hypercycle. Here, this notion only serves as a requirement on active perception, that the task accomplishment must be explained as global behaviour of component cycles of computation. There is no further indication as to what exactly are the computational processes that lead to the envisaged global behaviour. The notion of hypercycle may be multiply realised, on the basis of different ways of mutual support between sub-systems, as demonstrated by the differences between gaze control, Dickmanns' car, and other tracking capacities/capabilities.

At this point, discussions in the present thesis must develop an explanation of the hypercycle in active perception systems. This explanation must be considered to be an underlying principle common to all kinds of hypercycle (in active perception systems). This is seen in part in the topic of the next section, a newly proposed notion – internal cohesion.

6.3.7 Summary

The task-level emergence of active perception can be understood on the basis of four principles which are extracted from four models of life origin.

The first model is Rosen's (M,R)-system, in relation to which two points of task-level emergence can be established. One, while the **fundamental structures** of life origin are biochemical structures, the fundamental structures of active perception may refer to the stepwise computation of perceptual inputs leading to the guidance of bodily actions. The other point is that the task-level emergence grows from **baseline** to **elaborate** patterns of emergent phenomena, specifically from several small operation-specialist systems to a combinatory system, as exemplified by gaze control and Dickmanns' car.

The second model of life origin is Maturana and Varela's notion of autopoietic unity, which emphasises the importance of operational closure in understanding life phenomena. Related to this principle is that the basic computational cycle of task-level emergence consists in the comparison between collected information and the needed information which *insures* the previous outcome will really contribute to the required tasks. A striking point derived from this principle is that the systems of active perception are ultimately *pragmatist* systems.

The third model that gives hints toward the understanding of task-level emergence is Kauffman's autocatalytic network, which emphasises the requirement of self-sustenance for a minimal living system. Corresponding to this principle is a principle of task-level emergence, namely that the stepwise computation of active perception is grounded on the stable and continuing processing leading to the completion of a single step of information comparison, between the already collected information and the information needed for accomplishing a required task.

The last model is Eigen's model of hypercycle, which is an autocatalytic cycle generated from the connection of several component autocatalytic cycles. Similar to the generation of a hypercycle is the stepwise computation of a combinatory system on the basis of its sub-systems, such as the computation of Dickmanns' car based on the mutual support between several particular tracking sub-systems, as manifested in the control of generic schedules which link to each tracking subsystem by feedback loops.

6.4 Emergence as Internal Cohesion

This section discusses the generation of adequate guidance (for the required tasks) from the viewpoint of emergence.

As previously mentioned (see Section 6.3, page 227), the processes of internal cohesion take place at two levels – lower and higher. Those at the lower level concern the task-level emergence of a *single* system, such as attentive control of saccades or Adept. By contrast, those processes at the higher level concern the task-level emergence of a large system, such as Dickmanns' car, gaze control, tracking capacity/capability, or even the combination of all these systems. The processes that maintain internal cohesion at the lower level lead to the computation within a single small system. The computation at this level corresponds to Rosen's baseline patterns of emergent phenomena and Kauffman's notion of autocatalytic cycles. In contrast, those maintaining internal cohesion at the higher level lead to computation *across* systems (such as gaze control, tracking, or Dickmanns' car), which corresponds to both Rosen's conception of elaborate patterns of emergence and Eigen's notion of hypercycle.

The discussion in the previous chapter explained activeness – what makes active perception work – on the basis of exploitative control. Sections 5.2 and 5.3 discussed task identification and the arrangement of processes leading to designers' envisaged tasks. The discussions highlight the importance of small-sized operation-specialist systems, whose nature is discussed in Section 5.4 via the notion of quasi-functional modules and quasi-action modules (as opposed to functional and action modules). Such quasi-form modules are vitally important for the implementation of active perception, as previous arguments show, because they alone can fulfil the four main characteristics of active perception. Such modules contribute to active perception by providing four types of exploitative utilities, which together serve as the *guidance* for fetching further needed information in support of the required tasks.

It is not yet clear, however, as to how *adequate guidance* can be made available (by quasi-functional modules and quasi-action modules) in *support* of task identification and the arrangement of processes which leads to the accomplishment of the designer's envisaged tasks. The question, specifically, rests on the competence of generating adequate guidance in *autonomous* systems, which have neither built-in blueprints not inherent intention. A system with quasi-functional modules and quasi-action modules may well produce certain guidance, but it needs to explain as to *why* an autonomous system with such a repertoire can produce the adequate guidance leading to the (designer's) envisaged tasks. If it is neither a built-in blueprint nor inherent intention, what is it ultimately that constitutes the basis of that adequate guidance?

The previous efforts toward explaining this adequate guidance will be seen in a new light when they are considered in the context of emergence. Emergent phenomena need neither blueprints nor intentions. In addition, the previous established principles of emergence may shed some light on our present discussions. The above question may consequently receive a plausible answer when it is put in the context of emergence.

The course of emergence is by no means magical, however. There seems to be no such a thing as a first principle of emergence which is so comprehensive that from within it every useful notion can be derived. Conversely, additional subject areas may serve to elaborate our knowledge of emergence. The understanding of emergence may be topic dependent to a certain extent: that is, although there may be commonalities between the emergence of biological traits and that of cognitive capacities, there may also be differences. Previous understanding of emergence in biology may be elaborated by the knowledge of emergence developed from different subject areas.

Active perception can be seen as one of these subject areas. The distinctive nature of active perception, as manifested in the adequate guidance of task identification and process arrangement which leads to the required tasks, suggests the notion of *internal cohesion* as a ground notion of emergence, as we will see. To see it from another perspective, when we are in the process of deriving such a notion, the above question about adequate guidance will be understood in the context of emergence, which is a more feasible ground (than the discussions in previous two sections) for understanding generation in autonomous systems. Such a ground can be shaped as follows: the guidance for the required task is considered as adequate when, and only when, it is heading in the direction of the required task, and this is done by maintaining the *effect* of internal cohesion *between* various factorial conditions (including transformations of perceptual inputs and values of critical variables) *and* the stepwise guidance of sensory-motor movements.

6.4.1 Explaining the Emergence of Active Perception in terms of Internal Cohesion

Emergence and Cooperation. Global behaviour is generally conceived of as the *cooperation* of the components in a system in which emergence takes place (e.g. Forrest 1991). The cooperation, in turn, is subject to different principles depending on the related algorithms/mechanisms of emergence. However, the emergence with recourse to both dynamical systems and situated activities, which are subject to different mechanical principles, are commonly understood in terms of cooperation. The concept of cooperation seems to have been taken as the polar opposite to the concept of the instructions specified in the algorithms for characterising local activities. It is consequently merely a concept, without specifying exactly the mechanical principles or the conceptual exposition of emergence.

The emergence of active perception (at task-level), by conception, certainly falls into the category of cooperation. However, the discussions here are committed to further conceptual exposition, and we consequently introduce a notion – internal cohesion.

Internal Cohesion.

A Novel Notion. The term 'internal cohesion' in the present thesis can be defined as follows.

> **Definition of Internal Cohesion.** Internal cohesion is meant as the act of effectively composing all the forces relating to a particular system within an (artificial or real) organism which controls sensory-motor movements or bodily actions, such that those forces serve to arrange the *serial* steps of computation (in the derivation of guidance) in a way that reflects the various internal emphases of a given task.

To put it in the context of active perception, the notion of internal cohesion largely relates to two types of task – gaze control and tracking.

This definition needs elucidation by examples of different tasks of active perception. Regarding the tasks of gaze control, the relevant forces are the stepwise evaluation of visual inputs and the consequently derived guidance of sensory-motor movements. Relative to such forces, internal cohesion specifically refers to the act of a perceptual system that *arranges* the stepwise evaluation of factorial conditions, and consequently derives guidance of sensory-motor movements, with the effect that the needed information/guidance in support of certain bodily actions is properly collected. In the course of computation, the serial steps of evaluation manifest the emphases of the task engaged with, such as important visual features relating to that task.

Regarding the tasks of tracking, the relevant forces are the perceptual images under transformation and further linkage. Here, internal cohesion particularly refers to the transformation and integration of the factorial conditions in the perceptual inputs, for identifying *concrete* bodies quickly, with a view to keeping track of the targets and recognising them. In such a context, internal cohesion (as an act of composing forces) provides two kinds of guidance – the prediction of subsequent contours for further tracking and the transformation of the current target contours into corresponding bodily movements in support of catching the target. The ingredients of these two kinds of guidance are the emphases of the task here – tracking.

The Non-intentional Origin of Global Behaviour in Active Perception. Of course, internal cohesion as an act is not maintained as an effect of an intentional being, such as an homunculus. It is an effect of global behaviour between various computational mechanisms within the perceptual system concerned, such as the stepwise evaluation of visual features maintained by the attentive control of saccadic movements together with the subsequent pursuit movements.

Not a Conceptual Analysis. The above definition of internal cohesion is not simply a conceptual analysis imposed on the concept of cooperation (in connection to emergence). If the definition of internal cohesion resulted from the conceptual analysis of cooperation, then the concept of internal cohesion would simply re-state what was already known about the cooperative processes in relation to emergence. In addition, the cooperative processes relating to the task-level emergence of active perception would then necessarily fall into the category of internal cohesion, and consequently it would be impossible to have conceptual alternatives to cooperative processes.

Internal cohesion does not seem to result from the conceptual analysis of cooperation, for two reasons. First, the connotations of internal cohesion outstrip the concept of cooperation, because internal cohesion can be regarded as a *further* exposition of cooperation. As manifested in the definition of internal cohesion, internal cohesion is an act of effective composition of certain forces within an organism, and such an act is not an element of the concept of cooperation.

Second, there are indeed certain conceptual alternatives to task-level emergence related to the understanding of active perception, although they might be less plausible than the account of internal cohesion.

An attempt at explaining the task-level emergence in question is Steels' account of emergent functionality, according to which it is the *organism-environment interactions* that account for emergence, not the act of composing forces *within an organism*. These two accounts might not be incompatible, but they are indeed not conceptually identical.

Another example is the self-organisation grounded by dynamical systems theory, according to which emergence is brought about by the tightly coupling interactions between certain number of control parameters. Again, this is a different account, because the intra-organism forces in internal cohesion are not control parameters, and because the processes of composing forces may be different (and indeed *are* usually different[17]) from the differential equations characterised in

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[17] Certain implementations of active perception do not adopt dynamical systems, such as

dynamical systems theory.

Therefore, the account of internal cohesion provides new understanding of emergence beyond the conception of cooperation. Internal cohesion can be divided into two types, corresponding to different active perception systems: gaze control and tracking.

Type One Internal Cohesion - Gaze Control. The actual paths of saccadic and pursuit movements depend on the contingency of the visual scene, but the underlying mechanisms are fixed. Both kinds of movements have their respective control mechanisms, which are fixed, and a saccade is always followed by a pursuit movement – a fixed order. For a given task in different environmental conditions, the foveae are not directed to the same features in saccadic movements, nor are the resulting paths pre-determined, but the underlying mechanisms manifest fixed orders between the saccade and the pursuit, and between single saccadic movements. It is the computation involved that maintains the composition of the ordered processes. Specifically, the maintenance of order should be attributed to the *stepwise evaluation* of visual features maintained by attentive control of saccade and the *stepwise comparison* between expected features and the actual foveated features maintained by the pursuit. In the end, the ordered processes lead to the accomplishment of tasks. There is no intentional being, but only computational mechanisms, which serve to maintain the order.

As another example, in Adept (see Section 4.2.1, page 126), it is the computation of critical variables that manages to identify a free-space and lead Adept away from obstacles toward the target. A variety of critical variables are involved, such as the unit vector **T** viewed from a certain vantage point, the degree of curvature of the envisaged surface, and the curvature of the curve-section on the plane determined by **T** and the curve normal **N** of the given point **r**. The computation is subject to a serial order, which consists of three stages (1) detect-

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Adept, and the attentive control of saccadic movements. For those that do adopt dynamical systems, such as Dickmanns' car (see Section 4.2.2, page 132), dynamical systems theory is not the only mechanism subserving them, as the generic schedule of procedures is actually another implemented mechanism.

ing the surface shape of an encountered obstacle, (2) determining the free-space around this obstacle, and then (3) managing to determine the free-space between obstacles (figure 4.5). The serial order is clearly manifested. With a free-space identified, it is then straightforward for Adept to pass over the unmodelled obstacles and eventually reach the pre-specified goal. The computed values of those critical variables are available to further computation at later stages, with the effect of bringing about guidance toward the pre-fixed target.

Like saccadic and pursuit movements, the actual paths of Adept toward the target are subject to the contingency of environmental conditions. However, there are fixed serial orders of guidance (toward that target), which is not predetermined but consists of the computed variables at different stages.

Type Two Internal Cohesion – Tracking. The internal cohesion in the context of tracking is exemplified by Snake and the Kalman filter. Snake is a system of tracking that puts together various basic images (such as line, curve, angle) smoothly and quickly via an internal energy-minimising function, which is an autonomous mechanism. Between those basic images the energy-minimising function maintains linkage with smooth and continuous splines, for which even those basic images need to be slightly modified.

The result is the identification of concrete (rigid or elastic, stationary or moving) bodies for the targets, which are consequently identified in the surrounding objects. Because of the continuity between shapes, the identification of those concrete objects at one moment helps the identification of the same targets at the next moment. In addition, the identification of objects does not end up with a visual display, but contributes to bodily movements. Specifically, the perceptual information of target identification can be transformed into corresponding bodily actions in a serial order, in view of catching the target somehow (by grasping, bow and arrow, even by a missile – a more complicated case).

In brief, the internal cohesion in relation to Snake is maintained by an autonomous mechanism (i.e. the energy-minimising function), which provides both the contours of concrete bodies (for the current and next moments) and the transformation into corresponding bodily movements in the light of catching the target objects.

Similarly, the Kalman filter is a system of tracking that serves to provide concrete contours for the target objects at current and next moments, and it can be connected to mechanisms that transform the identified contours into corresponding bodily movements in view of catching the targets. A salient difference between the Kalman filter and Snake rests on the process of contour identification. While that of Snake is a synchronic function of a variety of basic images, the process of the Kalman filter is a diachronic function of certain external states, specifically a recursive function for stepwise evaluation of the computed values and comparison between those values and the previous estimate.

Such a difference between time orders does not affect the Kalman filter's maintenance of internal cohesion. The internal cohesion remains maintained by an autonomous mechanism, and the result is *concrete* objects in the visual states. As discussed previously (in Section 4.1.3 page 122), the Kalman filter is, in fact, more powerful and flexible than Snake, because the various forms of the Kalman filter subserve the tracking of more elastic and faster moving targets.

Three Characteristics of Internal Cohesion. In all the above examples, the actual paths of the gaze and actual contours under tracking are directed by the derived processes of the systems concerned, which respond to the unpredictable environmental factors. The emergence of those processes is maintained by a computation with the following three characteristics. The computation constitutes the internal cohesion of the system in question, in which appropriate guidance is brought about (a) at various stages (b) with different factorial conditions. Also the internal cohesion is (c) grounded in the stepwise computation of critical variables (or estimated features and knowledge gains in the Kalman filter), the evaluation and comparison between expected and actually achieved values.

Snake seems to be an exception, because its mechanism is a synchronic (hence not stepwise) function, to which the above three characteristics do not seem to be relevant. This may affect the applicability of these three characteristics, but this problem can be easily resolved. Remember that Snake becomes more flexible when it is realised in the form of the Kalman Snake, an instance of the dynamical Kalman filter (see Section 4.1.2, page 122), which is a stepwise function. When we talk about those three characteristics in connection with Snake, we specifically refer to the Kalman Snake. Yet, note that Snake itself remains an instance of internal cohesion.

Thus, the internal cohesion is neither controlled by an intentional being or designed on the basis of pre-determination, but is maintained by the underlying mechanisms in the perceptual systems concerned, with the above three characteristics (a) (b) (c).

Having defined the notion of internal cohesion, we have a firm ground from which to look again at the previously discussed issues about emergence and certain important properties of active perception.

6.4.2 Internal Cohesion as Exploitative Control

Activeness. In the previous discussions, the term 'activeness' is meant as what makes active perception work. Now, in the context of emergence, the notion of activeness is explained by reference to internal cohesion. Active perception is maintained by task-level emergence, as opposed to pre-determination or intentions, and that task-level emergence can specifically be explained in terms of internal cohesion. This point has already been demonstrated in the previous discussions about saccadic and pursuit movements, Adept, Snake and the Kalman filter. Since these are all the cases of task-level emergence (as opposed to learning) considered in the present thesis, the notion of internal cohesion is applicable to active perception in general.

Task Identification and Processes Arrangement Maintained by Internal Cohesion. In Sections 5.2 and 5.3 the argument concluded with the statement: both the identification of the required tasks and the arrangement of the needed information for those required tasks can be explained by reference to small architectures, on the one hand, and within-system relational structures and/or inter-system links, on the other. The emphasis in those sections rests on the small architectures. It is not yet explained, however, how adequate guidance can be achieved on the basis of those small architectures. This question can be answered now in terms of internal cohesion.

What was left unexplained mainly concerns relevance. Specifically, it was presumed that a limited repertoire of capabilities will naturally support the detection of relevant perceptual inputs and the derivation of relevant processes. However, the question how that relevance is achieved has really been left untouched. Given that this question must be resolved by appeal to neither pre-determination nor intention, the explanation of that relevance would be a difficulty without being put into the context of emergence.

The notion of internal cohesion can now serve to explain the aforementioned relevance. As analysed in the previous chapter, systems of active perception are subject to two types of task identification. Type one is mediated by representations in selection mechanisms, while type two falls into the category of performance. Task identification of these two types comprise both the detection of relevant perceptual inputs and the initiation of relevant processes, both of which need a small repertoire of capabilities. At this point, the relevance can be further explained in terms of the act of effective composition of all the forces relating to a particular system. The mechanisms of the system in question first circumscribe the range of the relating forces, and then we focus on those mechanisms, which serve to compose the related forces. In systems of active perception, the act of 'composition' *happens to*[18] be realised in the stepwise computation maintained by those mechanisms, as discussed in the examples and the three characteristics of internal cohesion.

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[18] The act of internal cohesion in different systems may be realised by different strategies of computation. It is an empirical issue as to what actually are the processes undertaken by the *act* of internal cohesion. That act is a general concept to be realised in particular systems.

Apart from task identification, the notion of internal cohesion also applies to the arrangement of appropriate processes leading to the performance of the designer's envisaged tasks. Again, the small repertoire of capabilities circumscribes the related forces of the system (of active perception) in question. The stepwise computation maintained by the mechanisms of that system serves to arrange the processes leading to the required tasks.

One might raise an inquiry as to why the mechanisms pertaining to the systems of active perception happen to maintain the stepwise computation leading to the required tasks. This is somewhat similar to the question why the V1 area of human cortex together with the extrastriate visual areas happens to be largely capable of maintaining the computation of visual forms (including colour, shape and motion), which must be seen as a contingent outcome of evolution. The answer would be: a result of evolution, those cortical areas just happen to do so. The resolutions of these issues, however, would require extended discussion, and are indeed beyond the scope of the present thesis. The next chapter will further consider the relations between those mechanisms of active perception and the environment. The discussions, in particular, will relate to the *learning* of certain capabilities of active perception. The issue of evolution will remain untouched, due to the limited scope of the present thesis.

The above widely ranging resolutions may be taken as topics of further researches, but here we are ready to discuss a particular topic – the relationship between internal cohesion and quasi-functional modules and quasi-action modules.

Quasi-functional Modules and Quasi-action Modules. Section 5.4 contends that active perception (as understood in terms of the four requirements stipulated by the notion of dynamic small modules) *must* be carried out by quasi-functional modules and quasi-action modules. Having introduced the notion of internal cohesion, the relationship between dynamic small modules and the quasi-form modules can be further understood, by seeing internal cohesion as a process of emergence *mediating* those two sides. The mediation at issue can specifically be understood with regard to its two sides. On one side, the task-level emergence of active perception (as characterised by the notion of dynamic small modules) must[19] take shape in the form of internal cohesion. On the other side, internal cohesion (as an act) is most likely supported by quasi-functional modules and quasi-action modules, as opposed to functional modules and action modules (i.e. competence modules – in Maes (1995)).

Side One: The Emergence of Dynamic Small Modules Must Take the Form of Internal Cohesion. Remember that the four requirements of dynamic small modules (see Section 5.3.2, page 161) are 1. presenting basic perceptual features, 2. dynamical combination of modules, 3. situational sensory movements, 4. stepwise sensory-motor movements with evaluation in each step. Because the requirements 2. and 4. concern the control within systems, the above four requirements apparently need the exploitative control of active perception, on the top of explorative control. Hence, the attempt to explain the task-level emergence of active perception must take shape in terms of processes *within* the systems of active perception. In addition, the *stepwise* sensory-motor movements must emerge from the act of *composing* the relevant processes, given that it is done neither by pre-determination nor by intentions. Regarding requirement 2 – dynamical combination of modules – the self-organisation of internal processes on the basis of dynamical systems, as demonstrated in Dickmanns' car, can be conceived as subserving the maintenance of effective composition of the within-system control forces. Thus, the task-level emergence of active perception must be fashioned in the form of internal cohesion.

Side Two: Internal Cohesion is Most Likely to be Supported by Quasi-form Modules. Quasi-functional modules and quasi-action modules seem to be more supportive than functional modules and action modules in explaining internal cohesion, as we will see.

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[19] Notice that our claim is weaker than the claim that the task-level emergence must *exclusively* take shape in the form of internal cohesion. According to our claim, it remains an open question whether there are other forms of emergence applicable to the emergence of active perception. Indeed, there is, as manifested in the self-organisation maintained by dynamical systems.

Remember that quasi-functional modules provide iterative (numerical) *transformations* of perceptual inputs (as is evident in the tracking systems, such as Snake and the dynamical Kalman filter), and the computation of *critical* variables (e.g. Adept). By contrast, quasi-action modules provide *guidance* for sensory-motor movements.

Also remember that internal cohesion is an act operating on the forces relating to a particular system which controls sensory-motor movements or bodily actions. In particular, within the systems of active perception such forces are operating on factorial conditions – i.e. the perceptual factors caught through sensors and transformed via numerical computation. The operation on such factorial conditions seem to be the privilege of quasi-form modules, as opposed to functional modules and action modules. Hence, internal cohesion is most likely to be supported by quasi-form modules. Accordingly, our discussions justify the previous claim – that the task-level emergence of active perception must take shape in the form of internal cohesion, and internal cohesion is most likely supported by quasi-functional modules and quasi-action modules.

6.4.3 Summary

The establishment of the above four principles account for several aspects of task-level emergence, but a core question of task-level emergence remains unanswered – why stepwise computation can lead to the accomplishment of a required task. The resolution of this question is fundamentally important for the explanation of activeness, which needs explanation via a novel notion – internal cohesion.

The notion of internal cohesion is introduced in this section in order to explain the task-level emergence of active perception. Internal cohesion is defined as the act effectively composing the forces within the systems of an organism, forces which operate on factorial conditions. Because such within-system forces are managed with orders, internal cohesion relates to exploitative control. As is demonstrated, this notion applies to all typical mechanisms adopted for implementing active perception (insofar as we review in the present thesis).

Previous discussions justify a central claim of the present thesis: that the notion of internal cohesion explains the task-level emergence of active perception. The justification needs to take account of two important aspects of active perception, as shown below.

First, the notion of internal cohesion explains task identification and process arrangement which leads to the production of guidance for bodily actions. Task identification of two types (i.e. by representations and by performance) both comprise the detection of *relevant* perceptual inputs and the initiation of relevant processes. The relevance can be explained in terms of the act of effectively composing all the forces relating to a particular system. The arrangement of processes leading to the production of guidance can similarly be explained, by identifying the arrangement of relevant processes with the act of effectively composing all the related forces, which is supported by the three characteristics of internal cohesion: appropriate guidance is brought about (a) at various stages (b) with different factorial conditions, and (c) is grounded by the stepwise computation of factorial conditions.

Second, the notion of internal cohesion explains how active perception is realised by quasi-form modules: the task-level emergence of active perception must take shape in the form of internal cohesion, and internal cohesion is most likely to be supported by quasi-functional modules and quasi-action modules.

6.5 The Role of Environment in Task-level Emergence

There cannot be a perceptual system without an environment. This point is obvious, because a perceptual system by nature is a system to perceive the environment. However, it is not so obvious that there cannot be an *active* perception system without an environment. A non-straightforward rationale of this latter point is that the environment stands as a seemingly covert 'organiser' of the active perception system. The environment is covert, ironically, because it is everywhere for any system performing in it, and is thus the nature underlying any machinery whatsoever. In addition, the environment can be seen metaphorically as an organiser, for a simple reason from the perspective of Brooksian robotics, namely that the environment is the world model – indeed the only model – of intelligence generation. A stronger reason, which is less widely noticed but may be more important, is that the environment stands as the reason to explain what a system feature *subserves*, even without posing an adaptationist stance.

If a system feature, e.g. the high resolution of foveae, is considered according to an adaptationist stance[20], a reason for the system's application in the environment would be drawn by consideration of the system's advantage for survival – i.e. the reason that the system *arose* in evolution. The adaptationist stance is controversial, however, as previously mentioned when we discussed the probable use of thalamic-cortical feedback loops of the LGN (see the footnote in page 152).

A non-adaptationist reason can be drawn, however, to explain not why a system feature arose in the course of evolution but about what it turns out to subserve, i.e. its *current use* in the environment. The difference between such a reason and an adaptationist account can be seen clearly in the current mechanical role of an evolutionary side-effect. Although the reason that it originally arose in evolutionary history is unclear, its current use may be evident. In a certain evolutionary time, organisms took advantage of that system feature, as manifested by its role in the present system. In this light (the current use of a system feature in the environment), understanding of an active perception system can take into account the role of the environment.

An important consideration is the impact of use on the understanding of emergence, according to the previous discussion of the inherent pragmatist stance of emergence (see Section 6.3.5, page 235), namely that the use of autonomous systems is *essential* to the understanding of (task-level) *emergence*. Hence, discussion of the use of an autonomous system (or the use of one of its system features) in the environment would contribute to the understanding of emergence.

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[20] For a detailed exposition of the adaptationist stance, please see Sober (1993).

6.5.1 The Notion of Inverse Ecological Niche

The use of a system feature can be understood through a novel notion to be introduced below: inverse ecological niche. With this notion this subsection introduces a new perspective to consider the relationship between the environment and the task-level emergence of active perception. This notion is defined as follows:

> **Definition of Inverse Ecological Niche:** The functionality of cognitive systems that supports organisms' survival and well living in their respective ecological niches, in particular the functionality of active perception systems that facilitates organisms in generating the perceptual guidance of bodily actions in support of their survival and well living in their ecological niches.

Given this notion, the considerations of environment are mediated by, and accordingly expressed in, the conception of ecological niche (see Section 2.2.1, page 26). So mediated, the notion of environment is put in the context of ethology and thereby enriched with various considerations regarding the *use* of perceptual systems, as discussed previously in Section 2.2.1. Specifically, via the notion of ecological niche, the environment of a species is understood in terms of its *behavioural* relationship with other organisms and the *physical* properties relating to its survival (comprising the habitat it resides in, the time it is active there, and the resources it attains there). In particular, this notion concerns a species' needs for *perceptual guidance* in its ecological niche. The functionality of active perception systems is thus connected to ethology, by considering how a species' survival advantages in its ecological niche are facilitated by the production of perceptual guidance, which is maintained by the explorative and exploitative control of those active perception systems.

To put the above analyses in intuitive terms, the notion of inverse ecological niche is introduced to explain how the active perception systems of a species *tune up* to survive effectively in its ecological niche. Such systems tune up in the sense that the emerging explorative and exploitative control *serves to facilitate* (by producing various perceptual guidance) the species' survival in its ecological niche. The discussions of this section, thus, will centre around the facilities brought about (as outcomes of task-level emergence) by such explorative and exploitative control in support of the species' survival in its ecological niche. In brief, this notion refers to the emerging facilities that support survival and well living in the ecological niche.

Explaining **Inverse Ecological Niche.** Above is the definition and relating conceptual analyses of the newly introduced notion – inverse ecological niche. The following discussions concern explanations as to *how* the species' survival and well living in the ecological niche is facilitated by the functionality of active perception, as manifested in its component sub-systems (such as the Kalman filter and the attentive control of saccades) and the internal cohesion of the processes maintained by such sub-systems.

6.5.2 Explaining Facilities that Support Survival and Well Living in the Ecological Niche

The above 'how' question mainly relates to three themes – 1. what tasks would be likely to arise, 2. what systems of active perception there would be, and 3. what information remains needed at a certain stage of computation. All these three questions connect respectively to a further why question, e.g. why those tasks are most likely to arise, etc.

1. Tasks and Ecological Niche. Only a limited number of tasks would arise, for any species in its ecological niche. This is generally because organisms must address the tasks which are highly *relevant* to their survival and well living in their respective ecological niches. Organisms would not waste their time pursuing the tasks that are hardly relevant to their survival or well living.

In addition, tasks seem to be subject to priority. Organisms might collect a great deal of perceptual information without actually initiating any task. For such roughly collected perceptual information, lots of tasks are possible, but only a few deserve actually to be pursued. The more important a task is for the survival or well living in the ecological niche the more likely it (this task) would actually be passed to the active perception systems. Consider the example of prey. The tasks of top priority are those which respond to the suspicious perceptual cues of their *predators*. The constantly interesting tasks (see Section 5.5.3, page 190) seem to fall into this category – those which are most likely to arise. They arise easily, without being mediated by intention or conscious attention.

For the tasks arising from intention, it seems reasonable to say that such tasks are also subject to priority. The more important an *enquiry* is for an organism living in its ecological niche the more likely it is to arise. Given the above, the pursuit of tasks seems to have strong roots/reasons in organisms' respective ecological niches.

2. Particular Systems and Ecological Niche. Every single active perception system seems to have its reasons in connection to its ecological niche. The reasons behind this point are discussed as follows:

Attentive Control of Saccades – For Directing Foveae to Important Visual Features. Foveae, as widely understood, are two tiny areas in the retinae of binocular vision with very high degree of resolution, which is clearly an advantage of vision. To take full advantage of this property, organisms need saccadic movements and their accompanying attentive control.

Because a large number of positions must be visited, saccades must be quick and computation of collected visual information must be stepwise. In addition, in order to collect exactly the needed information for the required tasks, neither too little nor too much, comparison must be maintained along with the gradually collected information. Addressing the most important visual features for the required tasks would definitely facilitate an organism's survival and well living in its ecological niche.

Pursuit Movement. The control maintained by pursuit movement can be seen as a facility which supports saccadic movements. As previously discussed (see Section 3.4.5, page 104), the computation of attentive control of saccades takes time, during which the target may have moved elsewhere, and consequently the saccadic movements lag behind the features expected by the attentive control of saccades. Apart from this factor, errors in the system of saccadic movements would make it difficult for the visual system to successfully gather the information expected by the attentive control of saccades.

Pursuit movements serve to cover the above problems of lagging behind and various errors. Hence, pursuit movement serves as a complement to the attentive control of saccades, in order to make the fovea really reach the expected visual features under real-time constraints. In other words, the functionality of the pursuit sub-system is to facilitate the saccadic movements to *accurately* reach the visual features expected by the attentive control of saccades. The accuracy of saccadic movements is very important for organisms to fetch interesting visual features, which would certainly help an organism to survive and live well in its ecological niche.

Four Types of Task-specific Utilities to Activeness Provided by Quasi-functional Modules and Quasi-action Modules. Each of the four types of task-specific utilities to activeness – judgement under uncertainly, using templates, using dynamical systems, and planning of actions – confers certain advantages of survival in the ecological niche.

The characteristics of ecological niche highlight the advantages of these four types of task-specific utilities. Without the harsh time pressure in the ecological niche, organisms need not undertake uncertain judgements which risk mistakes. It is reasonable to assume that without the need for quick guesses in the ecological niche (especially for pursuit movement and tracking) templates and dynamical systems might not be singled out in the course of natural selection.

Judgement under uncertainty presumes a certain specific time scale which constrains quick judgement. The time scales of subsequent movements (such as saccades and pursuit) must be subject to mutual cohesion between these two mechanisms. However, what exactly are the scales for these two mechanisms ultimately depends on the respective processes carried out in the ecological niche, particularly depending on how fine-grained the adopted heuristic knowledge is. Considerations cannot take too fine-grained heuristics because the judgement would consequently be deferred. By contrast, considerations also cannot take too course-grained heuristics because the judgement would accordingly risk inaccuracy. What exactly the right-grained heuristic knowledge is depends indeed upon how exactly and how quickly the most important characteristics of the ecological niche need to be taken into account in the relevant active perception systems. Hence, the characteristics of ecological niche have a substantial impact on the mechanisms of active perception.

In addition, the processes of planning have their roots in the characteristics of the ecological niche. For example, the critical variables manifested in the implementation of Adept, such as $\mathbf{T}$, $\mathbf{r}$, $\mathbf{N}$, κ_n, τ_g, serve to determine geographical paths step by step, which can be understood from a geometrical point of view (see Section 4.2.1, page 126): they are the variables concerning *curve and rigid* objects. The computation of *these* specific variables is critical for Adept to navigate in its ecological niche.

Additionally, for a robot fish to navigate in its ecological niche – water – the critical variables for maintaining navigation must include variables of *aquatic* conditions. The lesson is that the critical variables to be chosen for different organisms depend on the characteristics of their respective ecological niches.

Given the above, the four types of task-specific utilities serve to facilitate an organism to survive and live well in its ecological niche.

3. The Cooperation between Sub-systems. The cooperation between subsystems is vitally important for the maintenance of active perception, as is manifested in various active perception systems, e.g. the cooperation between various tracking sub-systems of Dickmanns' car, and the cooperation between attentive control of saccades and the control of pursuit movements. Different sub-systems serve to capture different characteristics of the ecological niche.

Different tracking sub-systems of Dickmanns' car address different tasks (e.g. lane keeping, avoiding obstacles, etc.) that happen in its ecological niche – the traffic. Those sub-systems cooperate by the generic control of various parallel tracking processes.

The saccadic movements are *followed by* pursuit movements, which serve as a complement to fine-tune against accumulated errors. These two systems have different emphases. The former system (the attentive control of saccades) focuses on the computation of important/interesting visual features, while the latter (pursuit movement) serves to *recover accuracy* from various errors.

For both tracking and gaze control, various sub-systems are needed for capturing different characteristics of the ecological niche. However, the manners of cooperation in these two systems are realised differently. The difference can be attributed to the different characteristics of ecological niche addressed in different systems. What is needed for Dickmanns' car is the generic control of various *parallel* tracking processes, while the gaze control needs to maintain the serial order of pursuit following saccades, with the latter *fine-tuning* the previous errors. It is reasonable to propose that the different manners of cooperation depend on different active perception sub-systems, which in turn reflect different characteristics of the ecological niche. Thus, the cooperation between component sub-systems has its root in the ecological niche.

Note that the processes mentioned in the above three points facilitate the task-level emergence of active perception. The emphasis in this section is that the facilities which support the task-level emergence of active perception have roots in the ecological niche. Thus, argument justifies the previously proposed relationship between the environment and the functionality of active perception systems proposed, as stated in the notion of inverse ecological niche.

6.5.3 Summary

Apart from Brooks' idea that the environment is the best world model (via the situated and embodied activities of organisms), this section introduces a novel perspective – inverse ecological niche – to consider the relationship between the environment and the functionality of cognitive systems. In the context of active perception, inverse ecological niche denotes the functionality of active perception systems that facilitates organisms generating the perceptual guidance of bodily actions in support of their survival and well living in their ecological niches.

The above perspective is justified by three points. First, organisms only seek to carry out the tasks that are relevant to their respective ecological niches. In addition, the more important a task is for the survival or well living of an organism in its ecological niche the more likely that task would actually be passed to the active perception systems.

Second, it is argued that the *control* of single active perception systems responds to the characteristics of ecological niches. Evidence can be found in the attentive control of saccades and the control of pursuit movements, which serve accurately to direct foveae to the important visual features of the ecological niche, and consequently facilitate the organisms' survival and well living in the ecological niches. In addition, it has been shown that the four types of task-specific utilities (judgement under uncertainly, using templates, using dynamical systems, and planning of actions) all have their roots in the characteristics of the ecological niche. In particular, organisms need to make judgements under uncertainty, and need templates of visual events, because of occasional harsh time pressure in the ecological niche. Moreover, the computation of certain *specific* critical variables reflects the specific characteristics of a species' ecological niche, as seen in the *aquatic* conditions of fish.

Third, as demonstrated by Dickmanns' car and the cooperation between saccadic and pursuit movements, different manners of cooperation depend on different active perception sub-systems, which in turn reflect different characteristics of the ecological niche.

The above three points together suggest that the functionality of active perception systems reflects various characteristics of an organism's ecological niche, and consequently facilitates the organism's survival and well living in its ecological niche.

6.6 Summary

This chapter considers the task-level emergence of active perception from three aspects. First, the discussion extracts several principles of emergence from models of origin of life for explaining the task-level emergence of active perception. The task-level emergence, according to the extracted principles, is understood by considering different emergent phenomena, from a minimal emergent phenomenon – the stable and continuing processing manifested in a step of information comparison – to a emergent combinatory system, which is supported by cooperation between different sub-systems.

Second, the serial order of various processes in an active perception system is addressed in the notion of internal cohesion, which proposes that the quasi-form modules respond to unpredictable environmental factors but still maintain effective serial orders between various processes of active perception. The various phenomena of internal cohesion are explained on grounds of the particular properties of sub-systems that cooperate.

Third, the notion of inverse ecological niche presents a novel philosophical explanation as to the relationship between environment and the functionality of a cognitive system. Within the context of active perception, argument justifies that the facilities subserving task-level emergence reflect the characteristics of the ecological niche.

Chapter 7

Philosophical Explanations of Emergence

This chapter concerns the philosophical implications of the conceptual foundations of task-level emergence which are derived in previous chapters. The focus of this chapter is on deriving philosophical understanding *from* those conceptual foundations, but not on seeking further philosophical expositions of the concepts currently in play, such as the definition of pre-determination, the distinction between general and task-specific models, and the attribution of *being active* to a variety of computer systems. Like the concept of life in artificial life study, such concepts may be very provocative for philosophical discussions and worthy of hot debate. However, due to the focus of the present thesis, further discussions along these lines can be rendered as avenues for further research.

The previous two chapters explain the task-level emergence of active perception through a variety of foundational concepts (or termed 'conceptual foundations'). This chapter aims to gather those foundational concepts together with philosophical notions, in order to provide a conceptual framework for understanding task-level emergence, with emphases on both the unity of emergence and the multi-fold emergent phenomena.

The discussion of this chapter begins with four salient philosophical accounts of emergence in connection to behaviour-based systems – Clark's explanatory interlock of emergence, the externalism maintained by Clark and Chalmers (1998), the role of internal representations highlighted by Clark (1995), and the enactive approach to emergence advocated by Varela *et al.* (1991). Discussion of these four philosophical accounts have two purposes – reviewing philosophical accounts relating to task-level emergence, on the one hand, and criticising those accounts on the basis of the understandings of active perception achieved in previous chapters, on the other.

Certain useful philosophical conceptions are extracted from those philosophical accounts and further developed to account for the envisaged unity of task-level emergence. Thus, based on Clark's conception of explanatory interlock two philosophical notions are developed: the *multiple* aspects of emergent phenomena and the understanding of explanatory interlock in terms of several *links* between knowledge sources. With these links, this thesis accounts for the integrity of multiple aspects of emergence phenomena.

The present thesis concludes with a discussion of the interdisciplinary study of cognition, specifically considering how to gain the unity of cognition through cooperation *between* scientific theories and philosophical explanations. The suggestion is that these two disciplines are mediated by certain common conceptual foundations.

7.1 Clark's Account of Emergence: Trinity of Emergence and Explanatory Interlock.

It is argued by Clark (1996, 1997) that emergence must be explained from a variety of perspectives, between which there must be explanatory interlock. At present he seems to be more or less alone in advocating the need for maintaining multiple stances in the explanation of emergence. Despite its being rarely advocated, the maintenance of multiple stances of emergence is a valuable endeavour for explaining the unity of emergent phenomena, the description of which is currently divided between many disciplines. This section discusses Clark's idea of maintaining multiple stances of emergence.

7.1.1 The Philosophy of Emergence

Three Explanatory Stances on Emergence. Three main perspectives are regarded as indispensable in understanding emergence. First, reductionism contributes to the understanding of a complex system from its components, as seen in the neuroscientific research on cortical areas, as manifested in the hypothesis of convergence zone discussed in Damasio and Damasio (1994). By reduction Clark does not mean Paul Churchland's notion of inter-theoretical reduction (Churchland 1981), but means the explanation of high-level phenomena via low-level phenomena, with the emphasis on the establishment of detailed understandings which specify components and their inter-relations.

Second, the *active* exploitation of the opportunities presented in the environment contributes to visual processing, in opposition to Marr's (1982) view. Clark refers to Ballard's (1991) example of personalised cues for efficient visual search. Such cues may be an outstanding colour (e.g. yellow) or a large object accompanying the target object (e.g. a table on which keys are left). Such cues link the target objects to other visual properties for easier detection. In addition, he also refers to an archetypal example of active perception – the attentive control of saccades – in order to emphasise the capacity of gaze control over a variety of visual cues. Clark's point is that the cues in the environment contribute to promoting successful problem-solving activity, hence visual processing is not purely a matter of transformation between internal images.

Third, the emergence can be supported by the *embedded* and *embodied* approach to mobile robotics, which was proclaimed by Rodney Brooks to be the implementation of intelligence without representations or internal models, as opposed to the understanding of intelligence in traditional AI. Robotics implementations in this approach demonstrate that global behaviour arises not from the search through an internal model but from tightly coupled organism-environment interactions.

The Trinity of Emergence and Explanatory Interlock. With the notion of trinity, Clark sees each of these three stances as forming a part of a complete and plausible account of emergence. That is, each of them is only plausible insofar as it is supported by its evidence, but none can be neglected in the understanding of emergence. Each stance is appropriate to a certain aspect of the explanation of emergence. The most plausible strategy for understanding emergence, he contends, is not to bet on a single stance, but to combine all three stances by 'explanatory interlock', by which the relationship between them can be somehow explained.

Clark's Conviction of the Importance of Multiple Explanatory Stances. Clark's standpoint on emergence is rooted in his attitude toward doing research in cognitive science. He sees each stance as helpful for the understanding of cognition, given its complexities. He regards different stances of explanation as different tools in cognitive scientists' tool kit. As he states: 'we will find ourselves adding new tools to cognitive science's tool kit, refining and reconfiguring but not abandoning those we already posses[s]' (Clark 1997, p. 175). A multitude of explanatory stances reflects various perspectives of understanding which help us to approach those complexities.

Different stances seem to have been treated as competing, by the academics, but this does not seem appropriate, especially for understanding the adaptive role of cognition. Research on the adaptive role of cognition brings to the foreground the fact that complexities reside intrinsically in the nature of cognition. When we do research in cognition, as Clark contends, different explanatory stances lift us to a vantage point, from which 'we will see a rather delicate and cooperative coevolution between multiple types of analysis and insight'. Without taking account of those complexities altogether we may be 'blind' to the 'adaptive success' of organisms. An anonymous aphorism he cites makes this vivid: 'if *the brain* were so simple that a single approach could unlock its secrets, we would be so simple that *we* couldn't do the job!' (ibid., italics Clark's). In other words, given the complexities of cognition, multiple stances of explanation would not be a deficiency of human understanding, but conversely a merit of accounting for its adaptive role.

Multiplism and Various Aspects of Cognition. Clark's notion of trinity and explanatory interlock, in the discussion of emergence, reveals an important property of cognitive complexities, that the various stances of emergence manifest several *aspects* of cognition. Unlike eclecticism, here it is not the case that various principles of cognition (such as functional specification, parallel distributed processing, active exploitation of environmental cues, and Brooks' embedded and embodied approach to robotics) apply to the same subject matter and stand in a relation of competition where certain principles are applicable while others are not. Rather, different types of emergence address various cognitive phenomena, which represent different aspects of cognition.

A notion of *various aspects of cognition* can be generalised from Clark's notion of trinity of emergence. This notion can be characterised below:

> **Definition: Various Aspects of Cognition.** Although cognition can be conceived as a unity with a certain degree of integrity, particular cognitive phenomena actually occur in a variety of forms, because of the heterogeneous particularities inherent in human experiences, perceptual modalities, domain knowledge, research methodologies, and study disciplines. Given the above, such cognitive phenomena are conceived as various aspects of cognition.

According to this definition, the notion of various aspects of cognition can be understood separately from the considerations of emergence. However, this notion can be regarded as a theoretical property of emergence: the various cognitive phenomena emerge in the course of evolution, in which organisms encounter various environmental challenges of survival and conquer such challenges when the cognitive features or capacities relevant to those challenges are configurated with the effect of generating effective and efficient responses to them. In this passage, the various aspects of cognition are put into the context of evolution, as the emergent phenomena resulting from the configuration of cognitive features or capacities in response to various forms of environmental challenges.

7.1.2 Multiplism vs. Eclecticism.

As Clark considers, the multiple explanatory stances need not stand in a position of competition, but can cooperate together. Although they are indeed shaped in different fashion they may be thoroughly compatible. He suggests that we aim to find interlock between different explanatory stances.

Eclecticism. Compared to his trinity explanation of emergence, Clark does not seem to present equally well in his notion of explanatory interlock, which is needed to support the three accounts of emergence, however. Without the explanation of interlock a difficulty for Clark's conviction in multiple explanatory stance would unavoidably arise: the envisaged interlock may not be graspable by humans at all.[1] That is, the complexities of cognition may actually prevent the envisaged interlock. If so, the adoption of a single explanatory stance would at least have the advantage of scientific unity.

Alternatively, as a weaker challenge a worry may arise when there is yet no interlock established between multiple explanatory stances, which seems to be currently the case. To wit, Clark's conviction might seem merely eclecticism – a standpoint simply gathering a multitude of different principles without accounting for their inter-relations.

Interdisciplinary Study. We may discuss the latter challenge first, for a weaker challenge is easier to meet. Philosophy may well go *before* scientific research as a light of scientific discovery. The expected interlock may be found easier, if it is really envisaged in scientific activity with the support of philosophy. Otherwise, we may persistently strive to bet on single explanatory stances

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[1] Concerning the biological understanding of consciousness, Colin McGinn (1993) contends that the relationship between consciousness and its biological nature is permanently baffling to human understanding.

and consequently leave the envisaged cognitive integrity in vain, given the intrinsic complexities of cognition.

By contrast, the former challenge can be met when certain inter-relations between the multiple stances are gradually achieved. However, this again seems to be a difficulty in philosophy. Philosophy stands at a high level and accordingly is hardly likely to answer the question *how* multiple stances converge. If scientists look forward to seeing an explanatory account of cognition from philosophy *and simultaneously* philosophers expect to interpret scientific evidence of cognitive integrity from scientific theories[2], then the endeavour for resolutions would likely to fall into the trap of chick-and-egg problem. This is a question left with the interdisciplinary study of cognition – a banner of cognitive science.

Multiplism and Various Aspects of Cognition. According to the aforementioned multiplism and the notion of various aspects of cognition, different stances on emergence can be seen as different explanations suitable for different aspects of cognition, which manifest different configurations of cognitive features or capacities in response to different environmental challenges. Such stances are compatible because they basically deal with different aspects of cognition. It might thereby be conjectured that different cognitive phenomena arise in organisms to facilitate their survival in different environmental circumstances. We may consequently name Clark's notion of trinity and explanatory interlock as *multiplism*, as opposed to eclecticism. Cognition is multiple because it is a solution to many different evolutionary problems. In analogy with clothes, people wear different clothes in different environmental (natural and social) circumstances. The complexities of cognition manifest various aspects of cognition that facilitate cognitive activity in a variety of environmental circumstances.

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[2] Notice that the collection of scientific *evidence* needs the guidance of scientific hypothesis, which in turn presumes insightful *understanding* of the subject matter. Scientists may hold an inquiry as to how the present multiple stances of emergence can be unified in support of their scientific discovery. They may seek support from inter-theoretic reduction, find no satisfactory resolutions, and then leave the question hanging unsolved, simply because it is basically difficult to figure out how to raise a hypothesis of cognitive integrity between diverse stances.

Multiplism, Explanatory Interlock, and Conceptual Foundations. The above argument for multiplism does not mean that different aspects of cognition are ultimately independent and consequently no interlock is needed at all. The reason is simple: different aspects of cognition support mutually the organism's maintenance of adaptability. Given that different stances of emergence explain different aspect of cognition, the interlock between multiple stances of emergence can be understood in a new light as the cooperation between different aspects of cognition. In order to ensure survival, organisms need the cooperation of various capacities, including organism-environment interactions, exploitation of environmental cues, parallel distributed processing and functional specification.

The remaining question, about the interlock of different explanatory stances, concerns how a variety of cognitive capacities integrate, i.e. cooperate together. Resolutions of this question can be pursued extensively at a small scale in various scientific proposals, as exemplified by Inui and McClelland (1996) (eds.), where the integration of cognitive capacities is well targeted within the same paradigm – connectionism – between different strategies of simulation.

At a large scale, it remains mostly a demanding issue as to how there can be explanatory interlock across computational paradigms, as shown above (page 265) between the reduction in Clark's sense, active exploitation of environmental cues, and Brooks' embedded and embodied approach to robotics. At this point, the demanded interlock may need discussion at the level of *conceptual foundations* of particular subject areas, such as active perception, as discussed in the introduction.

The multiplism introduced in this section can be seen as a philosophical framework for allocating a further developed conception – the links between different 'knowledge sources' – as will be discussed later (Section 7.5.2, page 305). The importance of such links is manifested in the comprehensibility of the unity of cognition, by accessing different aspects of cognition.

7.1.3 Summary

Section 7.1 introduces Clark's advocacy of the explanatory interlock of emergence: various aspects of emergence *must* be linked although they tend to be hard to bring together. Discussion shows that Clark's advocacy of interlock between various aspects of emergence can be understood as multiplism, as opposed to pluralism. Multiplism means different parts working together but allows that their links may unfold along with the process of emergence. In contrast, pluralism simply means different principles working together, which might be confused with eclecticism – a philosophy which does not address the links between various parts. Clark's notion of explanatory interlock can be conceived with the framework of multiplism, which suggests that the interlock of various emergent phenomena may unfold along with the process of emergence.

7.2 Externalism

7.2.1 The Origin of Externalism In Brooksian Robotics

Externalism Arises. Externalism mainly arises from the idea of intelligence without representations initiated by Brooks (1991a), an idea supported by the successful implementation of Brooksian situated robots. As a reaction against the computational paradigm adopted in traditional AI – orthodox computationalism – Brooksian robotics starts out with neither knowledge representations nor central symbolic processing (both adopted in traditional AI) but still succeeds in implementing a certain degree of intelligence (see Section 2.3, page 32).

A Conceptual Analysis. Externalism[3] has strong and mild versions. The strong version largely proposes that intelligence needs no support from internal

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[3] The term 'Externalism' is brought by Clark and Chalmers (1998), from Putnam and Burge's arguments about the truth-conditions of thoughts, into considerations about Brooksian situated robotics. Strictly speaking, what Clark and Chalmers (1998) coin is an abbreviation of 'active externalism', in contrast to the externalism maintained by Putnam and Burge. However, in the present thesis we use the abbreviation, because the Externalism of Putnam and Burge is not discussed at all. There should be no confusion.

representations (types 2 and 3) of world conditions. Rather, the embodied and embedded activities alone (see Section 2.3, page 34) suffice (to produce intelligence). This is held by Brooks (1991a) (in robotics) and Pessoa *et al.* (to appear) (in philosophy). The mild version states that intelligence to certain extent can solely arise from embodied and embedded activities while in certain circumstances internal representations may be needed. Most theorists and philosophers maintain this version of externalism, including Maes (1990b), Steels (1990a), Clark (1997), Clark and Chalmers (1998), and Varela *et al.* (1991).

Due to its background in Brooksian robotics, the term externalism does not strictly reflect its literal meaning, which would be a stance maintaining that intelligence is entirely established/shaped by *external* factors, as demonstrated by Gibsonian ecological approach to cognition by emphasising the *external availability* of visual guidance. Rather, it proposes that intelligence is grounded on *organism-environment interactions*, which specifically refer to embodied and embedded activities. In brief, the external in the context of externalism does not mean external *factors* but means external *interactions*. The reason that the literal meaning of the 'external' is not strictly followed is probably because the basic motivation of externalism is to stand as a challenge to cognitivism, which regards cognitive functionality as entirely taking place internally. Like Gibson's ecological approach to cognition, externalism sees the *source* of explaining cognitive functionality as *outside the brain*, as opposed to cognitivism. However, the discussions in this section are not simply limited to the sources (of cognitive functionality), but extend to the processes.

From Organism-environment Interactions to Emergence. The aforementioned success of Brooksian robotics sheds a new light on the understanding of intelligence, that intelligence is grounded not on elaborate task analysis by designers (as maintained in traditional AI), but instead on organism-environment interactions. More importantly, a previously untouched issue in traditional AI – emergence – seems to consequently gain an explanatory foundation: the real world inputs serve to determine *directly* the activation and inhibition of robots' internal states, through the situated and embodied robot control, without being mediated by pre-categorised data (as exemplified by the knowledge representations studied in traditional AI).[4]

The Explanatory Role of the Environment. Brooksian robotics has had another far-reaching impact – shifting the focus of discussions of intelligent processes from the search in internal models to organism-environment interactions. As Brooks conceives, if there must be a model lying between the robot and the world, '*the world is its own best model*' (Brooks 1991a, p. 417, italics original). Such a conception can be seen as the resumption of Gibson's ecological approach to studying cognition (especially perception) (see Gibson 1979), as is most evident in the research done by McFarland (1992), Horsewill (1992), and McFarland and Bösser (1993). Thus, a fashion in favour of the explanatory role of environment seems to arise, which is strengthened by the philosophical endorsement made by Varela *et al.* (1991), Clark (1997), and Clark and Chalmers (1998), as we will discuss later in this chapter.

Further Support from Dynamic Systems Theory. The idea of intelligence without representations (types 2 and 3) and the emphasis on organism-environment interactions are additionally supported, both in modelling and in theory, by the modelling of motor skills and motion perception on the basis of dynamic systems theory (Thelen and Smith 1994; van Geert 1994; Beer 1995; Kelso 1995; Port and van Gelder (1995) (eds.); van Gelder 1995, to appear; Buchanan *et al.* 1997). Such an approach is a computational paradigm different from orthodox computationalism, and distinct from Brooksian robotics.[5]

The following discussions focus on the philosophical conceptions which aim to explain organism-environment interactions. Regarding the strong and mild

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[4] Recall our discussions on the notion of emergence as opposed to pre-determination (see Section 2.6, page 64). In addition, a hard problem for traditional AI in explaining symbol grounding is accordingly easily waived, as Brooks claims.

[5] Together with PDP, Brooksian robotics and dynamic systems theory commonly constitute a computational reaction against orthodox computationalism, with regard to its notion of *central* processing. These three computational methodologies are consequently grouped as a *de-centralised* approach to cognition.

versions of externalism, if it is confirmed that internal representations (types 2 and 3) really play a role in the determination of cognitive functionality, the strong version of externalism is directly challenged. Discussion in the current chapter aims (among other goals) to confirm the existence of internal representations (types 2 and 3), and consequently further discussion only addresses the *mild* version of externalism.

7.2.2 Clark and Chalmers' Active Externalism.

The externalism of Clark and Chalmers (1998) is the view that certain organism-environment interactions qualify as *cognitive* processes, in addition to those taking place in the brain. Their goal is to claim that cognitive processes extend to parts of the environment and consequently the boundary of skin and skull cannot be taken as a criterion to distinguish between cognitive and non-cognitive processes.

Such a claim is grounded on the argument that cognitive activities can be enriched by manipulating situated activities or operational accessories, such as pencils and notebooks, spoken language, written words, graphs, calculators, computers, or anything in the environment that can be manipulated by the body (e.g. human limbs or even fish tail). To put it briefly, the body can exploit the environment to help the brain, with the effect of enriching cognitive processes. This stance is specifically termed *active* externalism because organisms must *manipulate their bodies* (necessarily in the environment) to initiate cognitive processes.

This stance, as they described it, seems largely plausible; however, the claim needs to be tempered and the argument needs augmenting, as we shall discuss. A worry is that the externalism in question seems to have been bought too cheaply. The following discussions will refine the claim to make it more acceptable, and will provide complements on the basis of our previous understandings of active perception.

The Argument on Account of Coupling. The argument is based on the notion of *coupling* which refers to the interaction between organisms and the environment in connection to cognitive processes. The archetype of a coupling relation is the embodied activities of situated robots. However, the argument of Clark and Chalmers' is derived not only from those activities, but relies on the manipulation of the aforementioned operational accessories (i.e. pencils and notebooks, spoken language, written words, graphs, calculators, etc.). Given this, their argument seems to be that *even* non-situated external processes can qualify as cognitive. Such an externalist position sounds striking, but has its difficulties, as we will see. Their argument can be roughly formulated as follows.

> (i) External processes employing accessories can run equally well (being portable and reliably accessible, i.e. non-detachable) as internal cognitive processes, and thus the external processes qualify as cognitive processes; accordingly, the external processes employing accessories are *substantially cognitive.*
>
> (ii) As a stronger claim, organisms can exploit environmental contingencies by situated activities; the consequently initiated external processes can serve to *drive* the ongoing internal processes and thereby *shape* the on-board cognitive routines.

Are Operational *Accessories* Really Substantially Cognitive? Consider point (i). True, if they are used properly, accessories can significantly *help* the brain to carry out cognitive processes. Otherwise, they would not be taken as accessories of cognitive processes. Accessories allow cognitive processes be more tractable, and consequently more complicated computation or communication can be maintained equally well, even more accurately and efficiently than what barely maintained in the brain without the aid of accessories. It can be granted that the detachability of operational accessories can be smoothly resolved. Along with the development of technology, it even can be granted that it is practically possible to significantly enhance the human-machine interface, to the extent that lots of machine utilities can be simultaneously managed as smoothly as those that happen in the brain. It is conceivable that someday the simultaneous use of various accessories could even be as parallel and distributed as human neural networks. This is a point Clark and Chalmers (1998) seem hesitant to raise, but can be granted. Even so, it still seems too hasty to jump to the claim that the external processes in connection to the use of accessories are *substantially cognitive*, as we shall argue.

Relating to this term – substantially cognitive – a misunderstanding might arise, that the external processes *per se*, without considering involving internal cognitive processes, can stand on their own to present the cognitive properties of the internal processes. This is a misunderstanding because external processes on their own, i.e. beyond the involving internal cognitive functionality, are merely *motor* manipulations of accessories, which can hardly be seen as substantially cognitive.

To consider it more specifically, external processes are cognitive only on account of the cognitive functionality of internal processes. Basically, external processes serve to support users by enhancing (e.g. in drawing pictures), retaining (e.g. in reading a book), or partially skipping (e.g. in running a computer program) the functionality of internal processes beyond what a user's brain itself can do. Without being used, accessories cannot function at all. There is hardly a sense in which the external processes without supporting internal processes can stand on their own and qualify as substantially cognitive. Hence, it might seem redundant to say that the functionality of internal processes further supported by accessories counts as substantially cognitive.

Strictly speaking, the internal processes involving in the use of accessories suffice to qualify those external processes as substantially cognitive. It is undeniably that operational accessories 'plus' internal processes are necessarily cognitive, and would perform *no less perfectly than* the internal processes without such a support.

By contrast, external processes on their own, i.e. beyond internal cognitive functionality, seem to be bare motor or sensory-motor manipulations of accessories, which can hardly be seen as substantially cognitive. The manipulation of external processes in this sense would be reading without understanding, moving a colour pen without actually drawing a meaning figure, and typing a keyboard without deliberating anything cognitive. This is certainly not what is meant by external processes. 'External processes' means organism-environment interactions, and certainly involve natural cognitive processes. Then, the question is in what sense can the claim 'external processes are substantially cognitive' be understood? There seems to be hardly a proper sense of understanding turning up to qualify the external processes of a user's as in themselves cognitive.

Some people may contend that the communication between a computer user and a computer program goes beyond the aforementioned non-cognitive activities. There seem to be abundant computer programs which exemplify this point, such as expert systems and the Latex compiler. The users of such programs simply type in certain simple codes, but the machine feeds back with seemingly clever indications or nice text editing. As one would argues, there must be certain processes responsible for the computer's feedback, which are indeed external processes (beyond the users) yet substantially cognitive.

Yes, the aforementioned processes are substantially cognitive, but do not seem to be purely external. A computer program itself is endowed with its designers' knowledge which should be attributed to their internal cognitive processes. Hence, beyond internal cognitive processes there are still *no* substantial cognitive processes. The aforementioned conceptual difficulty remains: it is hard to understand in what sense external processes can qualify as cognitive.

Perhaps, it would be better to choose a more conservative stance than directly assigning the label of cognitivity to external processes. To wit, the external processes of using operational accessories serve to *support* users by enhancing, retaining, or partially skipping the functionality of internal processes beyond what a user's brain itself can do. The cognitivity of external processes can be understood in this sense. External processes are indispensable in helping users to *extend* cognitive processes to the outside. In this sense external processes can qualify as a source of knowledge generation.

Does the Environment Drive or Shape Internal Processes? Consider the point (ii) (page 275). To argue for the importance of environmental factors in cognitive behaviour, Clark and Chalmers (1998) adopt certain analogical terms – 'shape', 'build', and 'drive'. But this provides their argument with only a little support, because those terms do not seem to explain much about the relationship between external processes and internal ones – specifically the effects of organism-environment interactions on internal processes.

To maintain their argument, they state that 'the plastic human brain will surely come to treat such structures as a reliable resource to be factored into the *shaping* of on-board cognitive routines' (pp. 9-10, italics added). The term 'such structures', according to the context, refers to the surroundings of words for a reader. In addition, they raise the example of fish swimming to emphasise the role of environmental factors in the development of swimming capacities. They state that 'the fish swims by *building* these externally occurring processes *into* the very heart of its locomotion routines', and that 'where the fish flaps its tail to set up the eddies and vortices it subsequently exploits ... creating local structures and disturbances whose reliable presence *drives* our [its?] ongoing internal processes' (ibid., italics added). In the argument the analogical terms refer to animate activities, but a difficulty will consequently arise: who are the driver(s) or the artist(s) that shape? It is certain that the authors would not really mean to explain the role of environmental factors in terms of the activities carried out by certain single persons (animals, or even vital forces), as the term 'drivers' or 'artists' *literally* implies. Rather, they seem deliberately aiming to explain that role in terms of the effects on internal processes brought forth by organism-environment interactions. Using the terms 'drive' or 'shape' is very likely to blur the real target of explanation.

The most specific explanations, in Clark and Chalmers (1998), are seen in two attempts. First, they assert that the brain develops in a way that 'complements' external structures and 'learns to play its role with the confines of a unified, densely coupled system'. So far, this is plausible. Further on, they claim that the environment constrains the way that a cognitive system evolves and develops, and this too is the case. Based on such reasons, they move on to claim that 'extended cognitive is no simple add-on extra, but a core cognitive process (p. 9)'. The problem is that there seems no other direct explanation as to *how* the environmental factors influence the making of internal cognitive processes.

Insofar as such a limited argument can reach we can try to extract two main explanations.

1. **Coupling is a Substantial Cognitive Process.** The external processes constitute a unified, densely coupled system, which is substantially cognitive.
2. **Organisms Exploit Environmental Factors.** Environmental factors can constrain the development (or evolution) of brain structures and internal processes because organisms learn to exploit such external factors and consequently circumscribe the external-internal coupled system.

The main thrust of the argument maintained by Clark and Chalmers (1995) is that organisms *exploit* environmental factors and thereby circumscribe the development of brain structures and internal processes. Roughly speaking, such an argument successfully *relates* internal processes *to* environmental factors, which is not seen in cognitivism. Unlike the previous argument about accessories, the argument here suggests a different role for external processes – that they are not optional but intrinsic to the functionality of internal processes. If organisms are isolated from their niche, their internal cognitive processes (as they are at present) may not arise at all. However, despite the intrinsic role of the environment, it remains hard to figure out what that intrinsic role is, and hence more specific explanations seem still required. At this point, our previous discussions on the role of the environment in the making of intelligent behaviour (see Sections 6.5.1, 6.5.2, pages 255, 256), can serve as these demanded complements. The argument we established in that previous chapter can be summarised in the following point:

Organism-environment Interactions and Characteristics of Ecological Niche are Intrinsic Parts of Internal Processes. External processes – the embodied and embedded activities – are *substantially mediated* by the environment. Unlike what accessories subserve, they do not merely serve to initiate and retaining internal processes. Such processes, hence, are not mere a *record* of internal processes.

Furthermore, through the external processes the ecological niche has a substantial impact on the *characteristics* of internal processes, as discussed in the notion of inverse ecological niche (see Section 6.5.1, page 255). A variety of mechanisms reflect various characteristics of this organism's ecological niche. In addition, the stepwise computation of the needed information for the required tasks manifests the organism's 'strategy' of carrying out those tasks in its ecological niche.

Both the mediation of the environment and the impact of the ecological niche on the characteristics of internal processes indicate that the organism-environment interactions must play a pivotal role in the making/emergence of novel capabilities/capacities. Roughly speaking, in the course of evolution and development characteristics of the ecological niche are reflected in the characteristics of internal processes through organism-environment interactions.

Organisms Interacting with Various Environmental Circumstances Through both Exploration and Exploitation (of the Environment). The argument of Clark and Chalmers maintains that organisms promote the functionality of internal processes because they *exploit* environmental factors. The term 'exploit (environmental factors)' seems to be roughly meant as 'take advantage of (environmental factors)', as manifested in the functionality of the fish tail which is described as exploiting eddies and vortices. It remains unclear as to whether the term 'exploit', regarding its common meaning in English, really means exploitation, as in autonomous agent research (see Section 2.4.1, page 38), or rather the combination of exploitation and exploration. Both exploration and exploitation have a bearing on the environment, and both are maintained by organisms' internal cognitive routines. However, they are different. Exploitative rules are items of heuristic knowledge that *characterise environmental factors* in internal processes; by contrast, exploratory rules are heuristic knowledge imposed on the explorative activities of autonomous agents, without characterising environmental factors within the internal processes of organisms.

To discuss specifically in the previous example – fish tail – it can be regarded as a single autonomous agent/system that interacts with the environment with both exploration and exploitation. As we previously discussed (see Section 2.4.1, page 40) in the example of learning navigation, explorative processes may move/navigate to the regions with the largest estimated error, address less explored states (such as visiting the least recently inspected positions), or maintain the planning action for exploring global states (instead of visiting the local state with the next nearest sensations). Exploitation is by no means the only way that an autonomous system can interact with the environment. As previously discussed, the capacity of navigation can take full advantage of the combination of them both. To understand their combination in the case of active perception systems, the previous chapters demonstrate several analyses and explanations.

7.2.3 Summary

Section 7.2 discusses Clark and Chalmers' externalism, which consists of two claims – that external processes of using operational accessories are substantially cognitive and that the environment drives and shapes internal cognitive processes. Regarding the first claim, arguments point to an inherent conceptual difficulty, and suggests an alternative – seeing the external processes of using operational accessories as *extended* from internal processes in the outside, by enhancing, retaining, or partially skipping the functionality of internal processes beyond what a user's brain itself can do. Regarding the second claim, the criticism concerns the explanation of the effects of the environment on internal cognitive processes. The criticism challenges the conception of 'drive' and 'shape', and suggests an alternative explanation, that the environment affects the evolution or development of internal processes by reflecting the characteristics of the ecological niche on the explorative and exploitative control strategies of organisms, as indicated in the notion of inverse ecological niche (which was introduced previously in chapter 6).

7.3 The Role of Internal Representations in Autonomous Adaptive Agents

The above externalist account of emergence generally stands as a reaction against cognitivism, especially regarding the emergence of adaptive capacities/capabilities in autonomous agents. Such accounts lead to scepticism about the role of internal representations, as Clark puts it with the name 'representational scepticism' (Clark 1995, p. 3). Clark contends that internal representations remain important not simply for off-line reflection or thought but also for the emergence of active capabilities. The point is that internal representations are not a hindrance to situated activities but conversely stand as their indispensable support.

Clark's re-affirmation of the indispensability of internal representations is a reaction to the strong version of externalism (page 271), but this does not make it an uncritical revival of cognitivism. As Clark insists, the temporality of internal representations must be explained. The commitment is to integrate cognitivism and externalism, with both being modified. It can also been regarded as a part of multiplism, specifically a particular explanation subserving the interlock between various aspects of emergence.

7.3.1 Reasons for Insisting on the Indispensability of Internal Representations for Explaining Cognition

The main reason that Clark insists on the indispensability of internal representations is the conviction that internal representations are *essential* to the nature of cognition. In this regard, Clark re-affirms a reason given by Beer (1995). That is, the overall 'representational story'[6] (of the external world) *must* be subject to de-composition, and hence there must be (the existence of) certain well-individuated inner sub-states or sub-processes which stand as bearers of the contents in the 'representational story' (p. 6). The parts can accordingly be interpreted/understood as contributing to the causal story of the world. In other

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[6] Clark's term 'representational story' may be understood as representational activities and their control.

words, both Beer and Clark take the semantic understanding and causal interpretation of the world as evidence supporting the existence of decomposed contents, which are primarily conceived as internal representations.

On grounds of the above reason, Clark sees internal representations as interpretations (semantic understanding) of the world. Briefly, Clark insists that cognition must comprise *content decomposition* of the world, while Brooks (1991) claims exactly the opposite, with his idea of intelligence without representations.

Clark's Definition of Internal Representations. According to the above two reasons that support internal representations, anything inside which contributes to better explaining the 'causal story' of the world can be regarded as an internal representation. The main concern in highlighting the contribution of internal representations seems to be not the mechanism and code of content decomposition, but the various individual internal states that can be identified for better (causal) explanation. As a consequence, internal representations can be identified as the distinct internal *states* that subserve content decomposition (which is indispensable for better explaining the world states).

Three Examples. Three example are provided by Clark to elucidate the role of internal representations in autonomous agents/systems. The point which underlies these three examples is that internal representations indeed *contribute* to the temporal response of autonomous agents/systems, and more strongly, that such representations are *needed* for that response. These three examples are described as follows.

The first example involves the environmental cues associated with single targets of visual search (i.e. cues that facilitate the search for certain objects in the environment), as seen in the yellow colour of Kodak film. Clark takes the yellow colour as a *personal* cue for those who search for the Kodak film. Because a personal cue is presumably an internal representation, this example is regarded in Clark's argument as evidence supporting the indispensable role of internal representations in active perception, specifically animate/active vision.

The second example involves the neurological mechanisms of the superior colliculus that subserves gaze control. Auditory-oriented information is transformed into visual-oriented information, specifically into the mapping of visual position and the corresponding sensory-motor movements, thus the superior colliculus contributes to the *eye*-centred coordinates. The point is that the transformation in the above mapping must be via 'a *distinct* on-board *equipment*' subserving the transformation of internal representations across modalities (pp. 9-10, italics added).

As the third example, motor emulation is necessary to exploit motor skills for higher speed, hence the fast proprioceptive feedback neural connections are identified as specific internal states supporting specific representational contents, motor skills.[7]

The above examples are taken, in Clark's argument, as evidence in support of the contribution and the indispensability of internal representations to the response in the real environment.

7.3.2 Discussion of Clark's Argument for Internal Representations

Clark's definition of internal representations assists in the integration of different computational paradigms. It can serve as a bridge between cognitivism and externalism, with regard to the temporality emphasised in situated robots and dynamical systems modelling.

On the one hand, the definition circumvents the two main characteristics of cognitivism – cognitive representations as *symbols* and the *central* processing of symbols. It consequently reserves a means of identifying representations in the de-centralised approach to cognition.

On the other hand, this definition identifies internal representations as inter-

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[7] There is no problem of understanding motor skills in terms of representations, because (as psychology textbook teaches us) they are procedural/implicit representations, as opposed to language-like/explicit representations. In addition, motor skills are simulated in PDP (see Churchland and Sejnowski (1992)), hence can be interpreted as distributed representations.

nal states, which is something common to situated robots and dynamical systems modelling, if only such states really subserve the bona fide[8] representations of the world (i.e. contents), as opposed to simply performing various behaviours which are intelligent-like from the *observers'* point of view. To have internal representations in this sense (i.e. contents) is indeed not a difficulty for de-centralised approach to cognition. Crudely speaking, except for those in Brooksian robotics all implementations of cognitive capabilities in autonomous agents/systems somehow fall into this category (i.e. adopting internal representations).

For example, the PDP has internal representations, as evident in the nodes and the parallel distributed patterns of node activity. Dynamical systems modelling also has internal representations, as revealed in the hierarchical and heterarchical structures of dynamical systems, and in the metaphors of dynamic systems theory, such as basin and attractors. In fact, dynamic systems theory sheds a new light on the general understanding of cognition (Kelso 1995), and in understanding psychological development, in particular (see van Geert (1994); Smith and Thelen (1993) (eds.); Thelen and Smith (1994)). As a further example, the exploitative control of autonomous agents, as seen in Steels (1991a) and Maes (1990b, 1995) presumes the existence and the explanatory role of internal representations. Hence, the de-centred approach to cognition, except for Brooksian robotics, indeed undertakes internal representations.

A Criticism of Clark's Definition of Internal Representations. The above definition is not entirely satisfactory, however. The role of those internal representations in the determination of cognitive activities has not been mentioned. In addition, that definition does not seem to apply to the type 5 internal representations (see Section 2.5, page 59), which are involved in the production of situated activities.

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[8] Compared to thoughts, the internal states at the *level* of machine operations are surely needed to implement symbolic computation, but they certainly cannot be seen as bearers of bona fide representations. If internal representations are instead defined as mere machine operations, the understanding of internal representations is trivial (not *bona fide*), because *any* computational mechanism (even that in Brooksian robotics) provides internal representations in that sense.

What is defined is but the existence of internal *states* that subserve the internal control of real-time response, without actually characterising the role played by *representations* in the production of cognitive functionality. There is no mention as to the forms and mechanisms of internal representations and their indispensability to the internal control. Hence, Clark's definition does not address the explanatory roles played by internal representations in the production of situated activities.

Without specifying those details about representations, the decomposition of representations and cooperation of them are conflated with a particular mechanism. For example, the internal mechanism that controls motor emulation is surely a system for internal control, but it is possibly the case that there cannot be any further decomposition of representations (type 5) and cooperation between them within the system. An example is the retrieval of skills which are previously acquired by rote learning. The representations of such skills do not seem to be decomposable, before they are further dealt with beyond rote learning (e.g. when certain parts are attended to).

The control of motor emulation is surely distinct from the control of other systems, as evident in single implementations, and hence different *systems* can be identified for explaining the integrated behaviour across systems. Given that the integration of different systems is an important concern in cognitive science[9] the identification of individual systems does help explain behaviour, but seems still a long way from understanding the decomposition of representations (types 1 to 5) and the cooperation between them within a single system.

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[9] This point – that the integration of different systems is an important concern in cognitive science – can be seen in Norman (1985) and McClelland (1996). Norman (1985) states that '... because the normal mode for the human is to interact, the studies of memory and language and problem solving and decision making in isolation address only one part of the mechanisms of human cognition' (p. 328). McClelland (1996) emphasises the importance of integration between modules. He traces the advocacy for integration between parts to the physiological psychologist Teitelbaum (1967) (*Physiological Psychology; Fundamental Principles.* Prentice-Hall), who pointed out the importance of reconnecting structure and functional contributions in order to see how they work together. Furthermore, McClelland himself asserts that 'it is encouraging to see just how much contemporary research builds on the contributions of the modularists in an effort to understand how the parts of the cognitive system work together' (McClelland 1996, p. 634).

Because that definition ends up with the *attribution* of certain temporal functionality to certain single networks inside organisms, it may risk being simply a re-affirmation of specific *systems* (such as neurophysiological networks) with specific functionality in the temporal dimension, which have long been confirmed. Identifying individual *systems* for controlling different real-time functionality does not seem to qualify as a further step toward understanding the internal *representations* (types 1-5) relating to real-time response within single systems.

For each single system, there can be certain internal states identified. However, the internal states of some systems have decomposable *contents* (type 5 representations, as seen in reinforcement reasoning), but those of some others do not (with only type 6 representations). Despite both kinds of system having internal states, the former systems have decomposable internal representations, but the latter systems do not.

In brief, the internal states of a single system may be either decomposable or not. The existence of internal states does not suffice to justify the decomposability of internal representations. As a consequence, the definition of (decomposable) internal representations in terms of internal states, like what Clark provides, may be inadequate. The explanation of the indispensability of internal representations to situated activities must go a further step *into* the decomposition of representations (types 2, 3 and 5) and the cooperation between them within a single situated system.

A Criticism of the Internal Representations Adopted in Animate/Active Vision. Staying outside a system of active perception cannot help see the decomposition of representations (types 2, 3 and 5) and cooperation of them within the system that serve as various facilities of active perception. This is a problem in Clark's considerations of active vision, with two examples of different importance.

Attentive Control of Saccades. The more important example is the attentive control of saccadic movements and its internal representations (types 2, 3 and 5). It is widely accepted in literature on active perception that this example can be taken as an evidence against the full-scale model database suggested in Marr's vision theory. However, merely mentioning the functionality of this system, as a whole, does not explain the indispensability of internal representations (particularly regarding representations of types 2, 3 and 5). Ballard (1991) mentions this example with the emphasis on its not being a full-scale internal model but a selective control, and hence active. There is, in that regard, still no justification concerning the indispensable role of internal representations (types 2, 3 and 5). Yet, it is argued by Clark that the attentive control of saccades relies 'on some internally represented surrogate' (p. 9), and hence he takes this example as evidence in support of the indispensable role of internal representations.

The problem is that the mere *existence* of this *system* does not reveal the existence of internal representations, let alone their indispensable role in the understanding of situated behaviour. To justify the indispensability of internal representations to the attentive control of saccades, argument should refer to the *mechanisms* of this control. The stance of internal representations would not be supported, unless *within those mechanisms* internal representations are confirmed as indispensable.

By contrast, when the *mechanisms* of the aforementioned attentive control are disclosed, as discussed in Robinson (1968, 1987), Clark's stance would become plausible: the attentive control of saccades really undertakes internal representations. Under the rough/gloss mechanism of visual attention (see Section 3.4.3, page 98), visual inputs manifest features of various weights, and one with the heaviest weight is singled out. Later, this mechanism compares the weight of the visual inputs in the visited position with that of other positions, while various weights are assigned to different visual features according to the required tasks. Those weights and their associated visual features are internal representations in connection to the required tasks, as regulated by the system of attentive control of saccades. Those internal representations are indeed indispensable to that system, as manifested in the architectures of that mechanism.

Without mentioning those mechanisms and their architectures, the internal representations of that system (from its outlook) seem to be darkened in a black box, within which nothing can be identified about the decomposition of representations and the cooperation of them in support of the required task.

Visual Cues. Regarding the less important example given by Clark (1995), certain environmental cues for visual search are associated with certain objects to facilitate searching in the environment. Cues (properties of objects) and objects surely can correspond directly to representations, as theorists (the third person) understand them. However, the association of cues with objects is not a direct proof of internal representations. It could happen to be the case that the association consists in a relation *between systems*, but not between the internal representations incorporated in a visual searching system. Specifically, when the agent intend to search for an object, say a Kodak film in the super store, she initiates the demand for a Kodak film in an intentional system, which also initiates a particular search system specifically established for quick search for the yellow colour, as an ad hoc association between systems. An arm like this would provide no justification for the indispensability of internal representations.

The point of our argument about internal representations is based on the nature of the category they fall in. The category of (*bona fide*) internal representations – i.e. contents – concerns what happens *within mechanisms* (e.g. the cooperation between representations), as opposed to pure reactive systems with type 6 representations. It is not a category concerning the *functionality* of the systems *per se*. When a system is identified with a certain functionality, say the functionality of wall-following implemented by Mataric (1990), there remains no justification for the view that the implementation of this system has actually used (*bona fide*) internal representations.

The emphasis of Ballard (1991) regarding those environmental cues, as opposed to the visual elaboration supported by internal computation, is the selective mechanism on account of a *object-centred* frame (coordinates), in contrast to the *observer-centred* frame undertaken in Marrian vision theory. The emphasis is not on *internal* representations, but instead on the *external* fixation frame. It is unclear in Ballard (1991) whether the external fixation frame must be represented internally. In fact, the external fixation frame is an *effect* of fixating on a fixed external point. When viewer moves forward, that point and the objects behind it move in the same direction. The simplicity consequently achieved is that the apparent velocity is '*proportional* to the distance from the fixation point' – a simple correlation detected by observer's self-motion while fixating on an external point (p. 64, italics added). This is an effect of *motion* in the real (external) environment, not an outcome of anything *represented* internally.

Ballard's stance on active perception emphasises the exploration of the environment rather than exploitative control, as seen in the AB perspective of active perception (see Section 3.2.1, page 82). In order to justify the role of internal representations in active perception, it would be better to seek support from the BC perspective, which emphasises the importance of exploitative control, and hence is a direct support for, and provides further explication of, Clark's stance on the internal representations *with* temporality.

The Indispensability and Importance of Internal Representations in Active Perception are Evidently Confirmed. Internal representations are really indispensable and important in active perception. The main topic of this thesis is the exploitative control of active perception with (internal) representations, which are not defined in terms of internal states. In fact, the concept of internal representations need not require a definition different from the common understanding in the de-centred approach to cognition.

All the examples and discussions can be seen as evidence in support of Clark's insistence on the need for internal representations in active perception. Here, there is no need to re-iterate the detailed discussions. In the subject area we previously surveyed and discussed – active perception – the indispensability and importance of internal representations is evidently confirmed.

7.3.3 Summary

Section 7.3 addresses the role of internal representations in autonomous agents in general, and in active perception in particular. The existence of internal representations in autonomous agents has been indicated by Clark (1995). However, his discussions do not account for the decomposition and cooperation of internal representations. At this point, discussions in this thesis complement Clark's position, by showing how internal representations serve to bring about various facilities of active perception.

7.4 Varela *et al.*'s Notion of Cognition as Embedded and Embodied Action

The above discussions concern the distinction between external and internal processes, specifically the distinction between organism-environment interactions and internal representations. Posing such a distinction relates to an inquiry about the *boundary* or *sources* of cognitive processes. While Brooks' strong externalism stands in a sharp contrast to cognitivism, Clark suggests that there might be no such a thing as a clear-cut boundary, in response to two similar *where* questions – where lies the boundary of cognitive processes, and where are the sources of cognitive functionality.

7.4.1 Terminologies – Embodiment, Coupling, and Enaction

The Notion of Embodiment. Another inquiry about the nature of cognitive processes is posed from a different viewpoint. It concerns neither the boundary nor sources of cognitive processes, but the connotations of cognition, which can be seen as responding to a *whether* question – whether there are such things as cognitive *representations* which can be circumscribed *independently* from world, biological structures, sensory-motor and bodily actions. This inquiry is raised and discussed by Varela *et al.* (1991), who pose a strong attitude against cognitivism, by claiming that cognitive processes intrinsically consist of a variety of things which do not fall into the category of representations: these things include the world, biological structures, sensory-motor and bodily actions, and cognitive and cultural context. In order to emphasise the importance of non-representational interactions, they adopt the term embodiment, which is meant in Brooksian robotics (see Section 2.3, page 34) as a radical reaction against cognitivism/orthodox computationalism. However, Varela *et al.* *extend* the meaning of embodiment, by assigning to it those non-representational things.

A Novel Ontological Stance. It is worth noting that the attitude of Varela *et al.* toward cognition differs from Brooks' not simply over the scope of the key term 'embodiment', but also on the understanding of *representations.* Brooks' emphasis is that cognition need not arise from representations; by contrast, Varela *et al.* reconstrue representations from a novel *ontological* perspective – a non-realist and non-idealist perspective. Varela *et al.* (1991) see their stance as 'a middle way between' realism and idealism (p. 172).

By the term 'realism' Varela *et al.* mean that the role of cognition is to maintain 'the recovery of a *pregiven* world' (ibid., italics added). Their stance would have been plausible, if this phrase pointed to naive realism, indicating thereby that they appreciate empirical realism – the realism that takes account of the contextual factors and cognitive interpretation in the understanding of the external world. However, it would be an overstatement, if consequently they argued for an ontological holism, that environment and organisms are conceptually inseparable.[10] Indeed, they seem to really do so, by seeing their work as an endeavour to restore continental philosophy (especially the phenomenology of Merleau-Ponty[11], as discussed later), which seems to have gone beyond the

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[10] As criticised by Clark (1997) and Varela *et al.* (1991) reflections against realist and objectivist views of the world risk obscuring the scientific value of the embodied and embedded approach, on the one hand, and risk introducing the problematic idea that 'objects are not independent of mind (Clark (1997), p. 173)', on the other. Apart from Clark's criticism, it is not hard to understand from a general (critical) realist point of view that objects *per se* are (ontologically) conceived by humans as independent from the mind, yet *the understanding of objects* are not subject to the relationship of direct correspondence: The mind interprets the perception of the independently existent objects.

[11] The orientation of Varela *et al.* (1991) in Merleau-Ponty's philosophy can be seen in the fol-

aforementioned critical realism in Anglo-American philosophy.

The (empirical) realist conception of representations, which is so far assumed in AI and cognitive science, affirms the *objective* existence of realities (entities and events) which can be seen as *epistemologically* grasped in the abstract relations of mental/conceptual contents. Such relations and contents are generally called representations. As mentioned above, Varela *et al.* do not challenge the notion of representations by simply shifting to idealism, another extreme of ontology. Rather, they attempt to develop a novel ontological position *between* realism and idealism.

The ontological stance of Varela *et al.* is as follows. They highlight the view that environment and organisms are mutually interdependent, which is described as a 'fundamental circularity' between environment and mind, and assert that beyond this circularity 'the worlds ... have no fixed, permanent substrate or foundation ... (p. 217)'. With this fundamental circularity they see human experience as 'groundless', for the reasons that 'we will always experience this familiar world as if it were ultimately grounded' and 'that we are "condemned" to experience the world as if it had a ground, even though we know philosophically and scientifically that it does not (p. 218).' In this passage, Varela *et al.* contend that the world does not have an objective ground.

In addition to the above assertion, they approach the relationship between world and mind by answering a related question: 'how could we not experience the world as independent and well grounded? (p. 217)'. Among the similar perspectives they refer to, one is typical and concise – David Hume's view. As they put it, Hume 'suggests that the idea of a continuous external world (like that of a continuous self) is a psychological construction ... (p. 231)', which is tantamount to the saying that there is no objective *existence* of a continuous

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lowing statement: 'We believe that it is time for a radically new approach to the implementation of Merleau-Ponty's vision. What we are offering in this book is thus a new lineage of descent from the fundamental intuition of double embodiment first articulated by Merleau-Ponty (p. xvii)'. The holist stance of Merleau-Ponty's can be seen in his idea: 'The properties of the objectivity and the intentions of the subject ... are not only intermingled; they also constitute a new whole (*The structure of behaviour* by Merleau-Ponty (1963), (p. 13); quote from Varela *et al.* (1991), p. 174).'

external world.

In sum, Varela *et al.* (1991) deny that the external world has a fixed and permanent substrate, and that the external world has an objective ground; by contrast, they appreciate the view that there is no objective existence of a continuous external world. This is not simply an epistemological stance as to how the human mind has a bearing on the understanding of the world, but a more radical ontological stance as to the ultimate existence of the world. As manifest in the above quotes, Varela *et al.* (1991) strive to eliminate the need for an objective substrate of the external world. As a consequence, they go beyond a spectrum of realist perspectives, and alternatively see the existence of the world as 'groundless', i.e. ontologically interacting with the mind.

The Notion of Coupling. To support their ontological claim, Varela *et al.* (1991) highlight the strong linkage between cognitive capacities and the world, on the one hand, and obscure the individuation of cognitive capacities, on the other. As regards the former, they emphasise the import of the aforementioned non-representational things (except for the cognitive and cultural context), by arguing that such things are *intrinsic* to cognitive capacities in the sense that cognitive capacities cannot be *independent* from such things. As regards the latter, they highlight the (cognitive and cultural) contextual effects of cognition and the *integration* of neural networks. For example, in their discussions of colour cognition, they highlight the contextual effects and the complication of integrated visual features[12]).

In general, for whatever they attempt to highlight or obscure, they coin a term – *coupling* – which means the strong and ultimate association of cognition with the aforementioned non-representational things, namely, world, biological structures, sensory-motor and bodily actions, and cognitive and cultural context. This term refers to both an epistemological and an ontological relationship between the mind and the world.

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[12] For this point, see Varela *et al.* (1991), pp. 157-171.

7.4.2 The Enactive Approach to Cognition

Varela *et al.* raise a novel stance on cognition – the *enactive approach to cognition* – as seen in the following paragraphs.

Enactive Cognition – Cognition Intrinsically Supported by Embodiment. On the basis of those non-representational things, the notion of coupling covers both organism-environment *interactions* (given the participation of the world), on the one hand, and the contextual effects and the complication of integrated cognitive properties, on the other. In particular, for referring to those coupling relations between cognitive capacities *and actions*, another term is coined – *enaction*. The notion of enaction specifically applies to two points, (1) bodily actions that contribute to perception, and (2) the emergence of cognition out of recurrent sensory-motor actions (p. 173). Because of the participation of such bodily actions and sensory-motor movements, Varela *et al.* (1991) raise the stance of *cognition as embodied action*, as an reaction against cognitivism. This stance is also named, more correctly[13], as the *enactive* approach to cognition.

Evidence. To support the enactive approach to cognition, Varela *et al.* (1991) provide several lines of evidence. Here, we mention only three in connection to perception. First, they refer to the Bach y Rita's[14] experiment of video camera, which transforms visual stimuli into a proprioceptive pattern on the skin to help blind people to recognise their environment. A condition intrinsic to this experiment is that the transformation across modalities would not proceed unless the user (the blind) maintains bodily movements.

In a second example, Varela *et al.* refer to Walter Freeman's experiment of

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[13] The term 'enactive approach to cognition' is more adequate than the previous term 'cognition as embodied action'. The emergence of cognition is understood by Varela *et al.* as *intrinsically supported/mediated by* embodiment, so cognition is enactive. However, the term 'cognition as embodied action' itself is conceptually deficient, because cognition is not tantamount to *action*. Also deficient is the term 'embodied action'. To describe action as embodied is a category mistake. Embodiment presumes action but the property of 'being embodied' is used to describe the cognitive capacities that are intrinsically supported by action.

[14] The name 'Bach y Rita' appears unusual, but it is actually so written in Varela *et al.* (1991) (p. 175).

olfaction pattern generation. Freeman inserted an array of electrodes into the olfaction bulb of a rabbit as a sensor to measure the global activity of olfaction while the animal behaved freely. The result was that no clear pattern of global activities took place in the bulb unless the rabbit was exposed to a specific odour several times such that chaotic activities could arise and subsequently converge on a coherent attractor.

The third example seems more an interpretation than direct experimental result. Varela *et al.* attempt to find an evidence of enactive cognition from Piaget's notion of 'circular reactions', a term cast in his constructive explanation of child development out of recurrent sensory-motor patterns. By directly identifying circular reactions (the generation of recurrent sensory-motor patterns) as enaction, Varela *et al.* interpret development as grounded on enaction.

These three examples can be seen as evidence showing the *fact* that perception requires bodily actions and sensory-motor activities.

Active Perception Can Serve as Evidence. Active perception systems seem to serve nicely as evidence for the above fact, that perception requires bodily actions and sensory-motor activities, for reasons already fully discussed in previous chapters. However, such a *fact* does not seem to well support the *notions* of enaction and embodiment, or the *stance* of 'cognition as embodiment', as shown in the following discussions.

Operational Closure vs. Coupling. An interesting point relating to the notion of coupling is that a previous view on an organism's *boundary* maintained by Varela and Maturana (1973) seems to be inconsistent with Varela *et al.*'s (1991) stance on an organism's boundary. To wit, the notions of operational closure and coupling appear to be mutually inconsistent: the former insists on the importance of boundary while the latter conversely endeavours to blur it. Note that those principles pertain to different domains. Operational closure applies to the *biological* regularities of living, while coupling is seen as *cognitive* capacities. One may consequently say that these two domains are subject to *seemingly* inconsistent principles. However, inconsistency would not arise between principles of different domains. That is, different domains may well have different principles, but inconsistency is a relationship between items of the same domain. Although they do seem to be different, the principles of operational closure and coupling are not really inconsistent.

By conception, there is no inconsistency in maintaining both operational closure and coupling in different domains. But even so, this does not guarantee that Varela *et al.*'s notions of embodiment, coupling and enaction are appropriate.

7.4.3 Criticising the Enactive Approach to Cognition with Examples of Active Perception

In order to criticise Varela *et al.*'s enactive approach to cognition (i.e. the stance of cognition as embodiment), let us first consider their notion of coupling,

Comparison with Clark's Notion of Coupling. Note that the term coupling is also adopted by Clark (1996, 1997) (also by Clark and Chalmers (1998)), but Varela *et al.* (1991) assign to it a wider range of relations. To advocate active externalism, Clark specifically uses the term coupling to mean organism-environment interactions. Where cognition is seen as grounded on the interactions between organism and environment, Varela *et al.*'s stance of 'cognition as embodied action' stands hand in hand with Clark's active externalism. Yet, Varela *et al.* (1991) do not, unlike Clark, try to *conceive* of organism-environment interactions in terms of external *sources* of cognition (as opposed to internal representations). In fact, they doubt that there *are* such things as internal capacities which are *independent* from the aforementioned non-representational things. Their intention is to bypass entirely the 'logical geography of inner versus outer', but alternatively suggest that cognition be conceived of as embodied action (p. 172). As they contend, cognitive capacities ultimately and intrinsically consist in embodiment (not in the Brooksian sense but in the extended sense), specifically in enaction. With the notion of embodiment and enaction they regard cognitive capacities as consisting neither in a 'pregiven' world nor in 'pregiven' categories (pp. 171-3). In brief, the same term – coupling – is used by Clark and Varela *et al.* in different ontological senses.

Active Perception Has No Ontological Implication. The difference between Marrian visual processing and active perception research rests on the difference between full and selective elaboration of visual information. The emphasis of active perception research is on *information* selection. There is no implication concerning the *ontological* status of the consequently understood world. However, the enactive approach to cognition insists on such an implication, by interpreting active perception as a direct evidence denying the independent existence of an objective world.

Partial Recovery of the Objective World. Using the selected information, partial recovery of *reality* remains possible. The active perception research may adopt a realist perspective. In fact, it does so, by understanding the external reality and providing guidance for bodily actions to execute in the external world. In active perception research the fact that perception is *active* is not taken as evidence to deny the objective reality. Accordingly, it need not presume the enactive approach to cognition.

Information Selection vs. Subjectivity. A confusion inherent in the enactive approach, in a nutshell, is to mistake information selection for the subjective shaping/interpretation of the world. This approach seems to assume that beyond the actively re-constructed world there cannot be an objective reality. This is indeed an over-interpretation, as revealed by the objectivity of a species' ecological niche, which relates to the *use* of active perception (see discussions in Section 6.5.1, page 255), and in turn has a bearing on the stepwise computation of active perception (see Section 6.3.5, page 235).

Although organisms do not understand the objective reality in the absence of interpretations, the organisms of the same species do have an objective ecological niche, which can be seen as such organisms' *world* – their *ground* of living. The world in such a sense is objective. Properties of ecological niche (see Section 2.2.1, page 26), which are subject to biological and ecological conditions, would not depend on organisms' subjective activities or perspectives. That is, the ecological niche circumscribes organisms' behaviour, but not the converse. Hence, organisms do have an objective world, even given the fact of *active* perception.

An Over-interpretation may be Conceptually Beautiful but Risks being Confusing. The account of embodiment and coupling seems conceptually neat and beautiful, with a strong flavour of wholeness and integration imposed on cognition and its relation to the environment. However, the beauty may be achieved at the expense of explanatory strength. In particular, an over-interpretation may be conceptually beautiful, but introduces extra difficulties because of the obscure conceptions it involve. For example, Varela *et al.* (1991) endorse Merleau-Ponty's idea by saying that 'we must see the organisms and environment as bound together in *reciprocal* specification and selection' (Varela *et al.* (1991), p. 174; italics added). This statement vividly paraphrases the notion of embodiment and coupling, but seems more figurative/metaphorical than explanatory. The coupling relationship between the world and the mind, as advocated by Varela *et al.* (1991), is well supported with respect to its epistemological aspect; yet, its ontological dimension does not seem to be consequently supported by the aforementioned evidence, and hence is overstated.

Consider the idea that organisms specify and select the environment. This idea can be squarely understood in the context of active perception, with organisms partially elaborating their perceptual understanding and thereby making judgement over the conditions of the surrounding world *under concern* (which are likely to be elaborated only partially). Hence, the term environment refers to the external conditions under consideration (which implies the active perspectives of organisms), and both specification and selection are explained in the context of information processing.

Conversely, consider the idea that the environment specifies and selects organisms. The conception of specification is best understood as the suggestion that the organisms' internal mechanisms *reflect* properties of their ecological niche (see Section 6.5.2, page 256). Selection may refer to natural selection. Hence, the term environment refers to ecological niche or milieu (which are objective), and specification is explained in that context, while selection is explained in the context of natural selection.

The analyses indicate that there is no basis to understand Varela *et al.*'s (1991) statement, in particular the phrase *reciprocal* specification and selection. The above two ideas (that organisms specify and select the environment and that the environment specifies and selects organisms) include three *ambiguous* terms – environment, specification and selection. Given this, these two ideas do not lead to a reciprocal relation. The statement made by Merleau-Ponty and endorsed by Varela *et al.* (1991) may consequently be confusing, although it sounds verbally neat and figuratively beautiful.

Are Exploration and Exploitation in Active Perception Enactive? – Unlikely. Notice that in previous discussions of Varela *et al.*'s stance the term 'enactive' applies directly to cognition in general, such as cognitive capacities and perception. Their argument for that stance seems to circumvent the discussion of enactive cognitive *processes*. If they discussed enactive (cognitive) processes, a program might arise. Their would-be discussions might reveal the existence of internal representations and processes, which could consequently be individuated. Although they can *interact with* (bodily or sensory-motor) actions, such representations and processes do not intrinsically *presume* those actions – a stronger stance – yet the enactive approach to cognition does hold that presumption, as discussed previously.

Ignoring the existence of internal representations and processes does not lead to their *in*existence. The previous discussions of Clark's usage of 'explicit' (see Section 2, page 279) showed that exploration and exploitation control active perception with external processes, on the one hand, and internal representations and processes, on the other. Remember that notions of exploration and exploitation relate to the stepwise computation of internal representations which closely interact with environmental factors. However, in previous sections and chapters there was no need to understand such close interactions through the notion of enaction, which presumes the ontological perspective that those perception-action interactions are intrinsic to cognitive processes. Internal representations and processes are clearly individuated in conception. They are conceptually independent of actions yet still theoretically interact with them. Compared to the notion of enaction, the individuation of internal processes and representations is better, because the actual representations and processes are identified and consequently the perception-action interactions are explained. To study the strong connection between perception and action need not be to *link* them by conception. It would be more appropriate to *separate/individuate* perception and action in conception but link them in theory, experiment, and consequent discussions.

A Concluding Remark. A lesson can be derived from discussing Varela *et al.*'s (1991) notions of embodiment, coupling and enaction. The nature of the *close* perception-action relationship must be clarified with separately *individuated*[15] representations and processes, and not blurred with Varela *et al.*'s notions of embodiment, coupling and enaction. Such notions seem to import a relativist perspective that cognitive representations are intrinsically *relative* to actions. The individuation would not eliminate the close relationship but conversely would *elucidate* the specific cognitive processes and their relationship with actions, as seen in the previous discussions surrounding the notions of exploration and exploitation. Before we can discuss cognitive representations, processes and actions, and their complex relations, they must be first individuated. Without individuating representations and processes it would be difficult to see that close relationship analysed or explained.

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[15] Being individuated means being *conceptually* identified, even independent of the closely interacting actions. When representations are individuated, their meanings need not be seen relative to their closely interacting actions.

7.4.4 Summary

This section discusses Varela *et al.*'s notion of enaction, which advocates an intrinsic connection between organisms and their environment, in particular the denial of an objective ground/substrate of the external world. A criticism raised in Section 7.4 led to a reconsideration of the notion of enaction, by affirming the reciprocally causal relations between organisms and environment but suggesting a way to preserve the objective status of the external world.

7.5 The Explanatory Interlock of Emergent Functionality – A Case Study of Active Perception

Discussion now moves on to the final topic – the explanatory interlock of task-level emergence[16] – which is vital for understanding the *unity* of emergent phenomena. Although it is hard to define and will be discussed in full later, the unity can now be roughly understood as the smooth functionality of certain emergent phenomena which is brought forth by gathering together the processes relevant to these phenomena.

Understanding this sense[17] of unity is important, because the emergent phenomena of a single system are usually understood according to different disciplines or various theoretical paradigms, yet they remain presented as *a single* system in reality. To put it specifically, cognitive phenomena, which emerge from biological structures, are studied from a variety of perspectives, such as the functional specification in psychology, the identification of cortical areas in cognitive neuroscience, PDP simulation, autonomous agent research (including both Brooks' embodiment approach and that undertaking internal representations). However, it is always important to explain the *integrity* of cognitive capacities *across* modalities, domains and disciplines.

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[16] The term 'interlock' orients in Clark's pursuit of 'explanatory interlock of emergence'. See Section 7.1, page 264.

[17] Another sense of unity is inter-theoretical reduction for understanding physical phenomena.

In particular, three aspects of emergent cognitive phenomena are *identified* by Clark (1996) for explaining their interlock – the identification of cognitive features in cortical areas, the exploitation of environmental opportunities by systems of active perception, and the emergent functionality on grounds of Brooks' embodied and embedded approach to cognition (see previous discussions in Section 7.1, page 264). Yet, apart from Clark's brief account, there is as yet no explanation as to the interlock of those three aspects.

7.5.1 The Notion of Different Knowledge Sources

Relating to the notion of various aspects of cognition (see previous discussions in Section 7.1.1, page 267) a similar but different notion can be introduced here – the notion of different knowledge sources.

> **Definition: Different Knowledge Sources.** The term 'different knowledge sources' means different origins of cognitive phenomena, from which (origins) cognitive processes/capacities are generated.

Different Knowledge Sources cf. Various Aspects of Cognition. The aforementioned two notions are similar because both largely concern many features of a unitary cognitive process. Yet, they remain different: various aspects of cognition are variously characterised *capacities or processes* while different knowledge sources are different *origins of generation* from which cognitive phenomena are brought forth.

The difference between these two notions is manifested in their respective extensions. The notion of various aspects of cognition refers to cognitive capacities/processes which are subject to different levels of description, such as the three aspects of cognition mentioned in Clark's notion of explanatory trinity of emergence – namely, cognitive capacities as specified in detail at lower levels of description, the capacities grounded on the exploitation of environmental cues, and the capabilities of maintaining situated activities.

By contrast, the notion of knowledge sources refers to epistemological *ideas/notions* or computational *strategies* from which cognitive capacities are generated. Examples of ideas are the considerations of adaptability vs. autonomy (which originate in the metaphysical contrast between the many and the one), and the contrasted explanatory perspectives (such as perceptual recovery/description, pragmatism, teleology, and mechanicalism). A further example discussed in this thesis is the notion of inverse ecological niche.

Examples of computational strategies are the strategy of situated organism-environment interactions, the computation on the basis of internal representations, explorative control, exploitative control, and various principles of task-level emergence (such as the completion of a single cycle of stepwise computation, and the comparison between collected information and that is yet needed for a required task). More complicatedly, computational strategies are also exemplified by the notions of dynamic small modules, combinatory systems, and the combination of exploration and exploitation.

Conceiving the Integrity of Task-level Emergence at Two Levels. A further difference between the notions of various aspects of cognition and knowledge sources is manifested in their respective levels (in the sense of parts/whole) of integration. Various aspects of emergent phenomena are integrated at the lower level by processes under the combinatory control of exploration and exploitation in various active perception (sub-)systems. By contrast, different knowledge sources are integrated at the higher level in three steps. First, the integration is manifested in a variety of *links*, as will be demonstrated later in this section. Second, on the basis of such links further integration can be maintained through activities of conceptual sophistication. Third, the conceptual sophistication as to the notion of internal cohesion and the conceptual foundations centred around it would manifest the unity of task-level emergence. Later discussions will justify the integration consisting of these three steps.

7.5.2 Links between Various Knowledge Sources

The present thesis presents a case study of emergent phenomena of active perception at task level, which can be seen as a response to Clark's advocacy of the explanatory interlock of emergent phenomena (see discussions in Section 7.1). However, it only addresses the latter two aspects of emergent cognitive phenomena among the trinity of emergence. Those two aspects have been discussed at length in the present thesis, with certain emergent phenomena beyond Clark's identification being isolated. As shown in previously chapters, the course of task-level emergence involves various types of task-specific utilities and various steps of process, yet each active perception system still presents a well integrated cognitive functionality.

Below are four dimensions of integration between different sources of processes. Each instance of integration, e.g. the integration between situatedness and representations, manifests a **link** between two sources of process. Although all links commonly show integrity between the processes of different sources, different links may be realised in different ways. As a rule of thumb, for different aspects of cognition each aspect (of cognitive phenomena) may have its pertinent type of linkage between the processes of different sources. Different types of linkage are realised in accordance with different system architectures and different theoretical descriptions. Although those differently realised links may be rather technical and consequently difficult to conceive for people in different disciplines, the discussions of the previous chapters provide a set of conceptual foundations from which to explain such links. The integration manifested in each of these four dimensions shows that the links between different sources of process, those between different computational strategies, and those between different epistemological accounts (e.g. mechanicalism vs. pragmatism), have been pursued in the previous endeavour to build conceptual foundations.

1. Integration of External *and* Internal Processes in the Determination of Task-level Emergence. According to the exposition of previous chapters, task-level emergence is determined across the boundary of skin and skull. Even a species' mechanisms that realise task-level emergence reflect various characteristics of its ecological niche.

- **Situatedness** *and* **Representations.** Both embodied and embedded activities (which are emphasised in Brooks' situated approach), on the one hand, and internal representations, on the other, are used in active perception systems to realise the task-level emergence. It has been demonstrated that these two knowledge sources cooperate together in support of the smooth functionality of task-level emergence.

  The links between situated activities and the computation based on internal representations does not seem to be describable by a single common conception, but rather is *multiply realised*, depending on the architectures of different systems. For example, Maes (1990b) links these two sides by the energy spreading across competent modules. The attentive control of saccades links saccadic movements and visual features by the comparison of weights between different visual features. Snake adopts energy control between internal images, while the dynamical Kalman filter adopts dynamical systems theory to link the values of control parameters.

- **Environment** *and* **Computation.** The environment relates effectively to the computation maintained in an active perception system, as manifested in the notion of inverse ecological niche (see Section 6.5.1, page 255). Unlike cognitivism, active perception research does not see the environment as detached from internal computation. Unlike Brooks' situatedness approach, active perception research does not understand the contact between environment and organisms simply in terms of contingent activities. Rather, they are connected in the form of representations. The characteristics of ecological niche are reflected in the stepwise computation which leads to the accomplishment of required tasks.

  Explanations as to how each characteristic of the ecological niche reflects on organisms' computational mechanisms may need to be put in the context of developmental or evolutionary theories. Again, the links between environmental characteristics and organisms' computational mechanisms does not seem to be explainable with a single conception, but is more likely multiply realised in various theoretical descriptions, with different theoretical descriptions applied to differently generated mechanisms in the course of development or evolution.

The observation that the processes of task-level emergence closely link up with the environment sheds light on the problem of explaining representations – the grounding problem of representations.[18] Based on our previous understandings of task-level emergence, this problem can be explained in terms of both embodied and embedded activities, on the one hand, and the reflection of ecological niche on computation, on the other.

In the course of task-level emergence, the across-skin computational activities consist in two contrasting strategies: evolution brings characteristics of a species' ecological niche *into* its active perception systems (in the form of built-in heuristic knowledge), and the on-line computational mechanisms can set up several heuristics to explore various circumstances of the environment.

- **Across-skin Computation Through both Exploration *and* Exploitation.** Computation for task-level emergence, which leads to the accomplishment of required tasks, adopts *both* exploration and exploitation, beyond what Clark indicates: organisms exploit the opportunities in the environment. That is, organisms not only exploit their ecological niches, as seen in the heuristic knowledge of the environment and the events in it (such as characteristics of how birds fly and how prey hide themselves), but also explore their environment, as seen in Ballard's notion of an object-centred frame, based on which organisms' gaze control becomes simpler and easier.

  The linkage between exploration and exploitation is subject to different

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[18] A similar formulation of this problem is posed by Putnam (1994) as the *hook up problem* – how the perceptual processes on the basis of organisms' perceptual systems effectively hook up to the external world. That problem raises an inquiry as to the *linkage* across an organism' natural boundary – skin and skull.

architectures of implementation in different systems. Different systems may need different manners of cooperation to link these two sides of the trade-off relationship.

2. **Gradual Formation of *Global* Behaviour on the basis of Various Principles.** The course of task-level emergence involves many steps, which may be subject to different principles. A *variety* of principles are needed, because tasks of active perception seem to be so complicated that they would not be accomplished without such different principles. Yet, different principles are even needed to explain the accomplishment of a *single* complicated task, such as gaze control.

- **Emergence is Subject to a Variety of Principles.**

  A variety of principles are needed for the accomplishment of tasks with different degrees of *elaboration*. As previously demonstrated, certain simple small active perception systems suffice to carry out computation for accomplishing simple *single* tasks. At this point, the computation is required to be grounded on two principles of emergence. The first is the 'baseline' phenomenon of task-level emergence: a minimally stable and continuing collective phenomenon. The second is the stepwise computation with the comparison of the previously collected and the still needed information, a process that leads to an 'autopoietic unity' in the sense of the accomplishment of a required task (see Section 6.3, page 227).

  Further on, the course of task-level emergence tends to become more 'elaborate' for certain complicated tasks, such as gaze control and the tracking capacities/capabilities for various perceptual features. The task-level emergence for such tasks needs to be realised in *combinatory* systems, such as Dickmanns' car and the human system of gaze control, which comprises six sub-systems (see Section 3.4, page 97). To accomplish those elaborate tasks smoothly, a combinatory system needs to bring forth a 'hypercycle' of computation.

- **The *Internal Cohesion* of Stepwise processes – For Computing *Various* Perceptual Features and Environmental Factors.**

  The computation for accomplishing required tasks must take account of a huge number of perceptual features and environmental factors, but a single active perception sub-system can only compute a very small (even tiny) number of those features or factors. Hence, computation is necessarily stepwise. The stepwise computation, when taking account of so many features and factors, must be capable of actually leading to the execution of the required tasks. So, the stepwise processes of computation are *required* to show *internal cohesion* across computational steps. This requirement applies to not only a combinatory system but also its sub-systems.

As discussed above, a global behaviour (of task-level emergence) is by no means only subject to a single principle. The behaviour is stepwise to address the complication of the perceptual world, yet the stepwise processes maintain internal cohesion to accomplish the required tasks smoothly and correctly.

- **Adaptability *and* Autonomy.**

  The stepwise computation manifests a 'metaphysical beauty' of integrating both *many* and *one*, as demonstrated in its taking a variety of perceptual features and environmental factors yet accomplishing required tasks smoothly and correctly. In particular, such beauty is realised in the simultaneous achievement of *adaptability* and *autonomy* of emergence, which are two requirements of emergence usually subject to a trade-off relationship (see Section 2.1, page 18): an active perception system is well adapted to the complicated and changing environment, yet this is fully maintained within the coverage of its autonomy. By maintaining internal cohesion, an active perception system can arrange its computational processes in order to respond effectively to the complicated and changing environmental conditions.

3. Linking Perceptual Features and Motor Actions. In the central nervous systems of organisms, both perceptual systems and motor systems take shape in the form of (real) neural networks. Despite being similar neurophysiological structures, those two kinds of systems are largely studied with different emphasises of capabilities. Perceptual systems derive *functional specification* of perceptual features, which are *easy* to understand using the category of representations, be they symbolic or distributed.[19] By contrast, motor systems maintain procedural skills, which are continuous, hard delineate through functional specification, and so seem *easier* to study on the basis of their *performance.*

Although in reality both perceptual and motor systems are well integrated, as demonstrated in hand-eye coordination, computation via functional specification and computation via performance seem to be different computational strategies. When the integration between perceptual and motor systems is required, a question naturally arises as to which strategy most suits the connections between them – either functional specification or performance.

The previous chapters show that such a dichotomy may evaporate given the mechanisms of *quasi*-functional modules and *quasi*-action modules, both of which serve to compute the *factorial conditions* of the perceptual features and the guidance for sensory-motor or bodily actions (see Section 5.4.1, page 176). Specifically, the computation of factorial conditions concerns the derivation of both perceptual *features* (by quasi-functional modules) and the perceptual *guidance* for sensory-motor or bodily actions (by quasi-action modules). Because such features and guidance both fall into the category of factorial conditions, such conditions form a ground on which those features and guidance are well connected to each other. As a consequence, quasi-functional modules link well with quasi-action modules without a gap between perceptual *functions* and motor *actions.* Active perception systems, thus, play a pivotal role in encompassing the different emphases on functional specification and performance.

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[19] The functional specification with distributed representations can be seen as *innate* capacities, in the sense of Quartz (1993), who criticises the fact that most neural network simulations are innate because of a designer's specification of tasks.

On the one hand, active perception systems connect to functional specification of perceptual features, because the selected perceptual information itself may be further computed to form full-fledged perceptual information. On the other, such systems bring about perceptual guidance to facilitate bodily actions. Active perception systems thus constitute a joint which connects two systems to maintain separately but gather together the perceptual features and motor activities. Along with the course of task-level emergence, both perceptual and motor systems will bring forth more and more perceptual features and motor activities. Most important, the generated perceptual features and motor activities go hand in hand, demonstrating the interlock between those two systems.

It is worth noting that the aforementioned separately maintained perceptual features and motor activities may be computed according to different paradigms, given that the previous discussions did not set constraints on the computation of the selected perceptual information and the guided bodily actions. It is not hard to realise the compatibility between the computation maintained *within* active perception systems and the *further* computation of the selected perceptual information. Although the computation with active perception systems is surely grounded on factorial conditions, the further computation may take advantage of *any* useful computational paradigm, including standard Marrian vision theory. Compared to the computation of perceptual features, the computation of guided motor activities seems less straightforward, because between the aforementioned perceptual guidance and the further elaborate motor skills certain other mechanisms may be needed.

4. Linking Different Bases for Explaining the Generation of Perceptual Understanding – Perception as Recovery/Description of External World, Pragmatism, Teleology, and Mechanicalism. Perception, be it understood by Marrian vision theory or by active perception research, *intrinsically* serves to recover the external world. Otherwise, perception would have no objective grounds, and consequently becomes hallucination. To put it plainly, perception essentially serves to report or describe the external world, despite the indispensable involvement of interpretation. The characteristic difference between the two perspectives just mentioned concerns whether to recover the world with full elaboration or with specific emphases. It is a common assumption that the faculty of perception must be explained on account of its functionality – the recovery/description of the external world.

Apart from the recovery of the external world, pragmatism – which concerns the consequence/application of a system – seems also salient in the context of active perception. As previously discussed (see Section 6.3.5, page 235), the content of the perceptual scene (i.e. the perceptual understanding) is organised based on its consequences – specifically, the contributions of its ingredients to the required task. The perceptual systems, that is, not only serve to report/describe the external world, but also subserve the required tasks on account of the consequences of the would-be collected (or even generated) information and the subsequently generated perceptual scene. Hence, it is not incorrect to say that task-level emergence essentially presumes a pragmatist ground.

Given the above, the perceptual scene not only presents descriptions of the external world, but also brings about the consequences of its ingredients for the required tasks. Perceptual understanding subserves both description (of the external world) and application (to the required tasks). These two dimensions are consequently linked.

A comprehensive explanation of the generation (task-level emergence) of active perception would need to take account of these four categories – description, contribution to tasks, intentions and mechanisms – without explaining any of them *away*.

The previous chapters show the existence of those four explaining categories in active perception systems. Firstly, partial elaboration with emphasis and interpretation on the intrinsic functionality of perception provides description of the external world.

Secondly, the category of application plays a role in explaining stepwise computation. Specifically, the stepwise computation must insure the next step of sensory-motor actions or internal computational processes, by comparing the collected information with the information needed for accomplishing the required tasks (see Section 6.3.5, page 235). Generally speaking, the mechanisms of a species' active perception systems reflect the characteristics of its ecological niche, as discussed previously with the notion of inverse ecological niche (see Section 6.5.1, page 255). Hence, the previous discussions in the present thesis have forged a link between mechanisms and application/consequence, which can be seen as a link between mechanicalism and pragmatism.

Thirdly, the category of purpose is indispensable in understanding active perception, because it is fundamentally a faculty aiming at carrying out *tasks*, which manifest organisms' intentions and goals. The linkage between tasks and mechanisms of active perception systems is seen in the notion of *task identification* (see discussions in Sections 5.2.1, 5.2.2, pages 145, page 155). That is, intentions and goals arise from outside an active perception system but can be identified within the system. The identification of tasks is the beginning of stepwise computation. In other words, active perception systems begin with the commitment to tasks. Whatever is described in the perceptual scene, the perception subserves certain tasks. Those tasks manifest the related intentions or purposes of perceptual activities. Because active perception systems begin with and subserve certain intentions/purposes, it is not unfair to say that there is a teleological dimension[20] to active perception.

The purposes and goals are not imposed on the active perception systems by divine fiat, but by organisms themselves. Specifically, tasks arise either in the intentional systems of organisms or in the heuristic knowledge implemented in their exploitive control (such as pursuing water and avoiding toxic substances), as mentioned in Section 5.2.2. In other words, tasks either take the form of transient goals or are shaped as heuristic knowledge, which may not be amendable. It is worth noting that the organism is not committed to the arising goals originally and permanently, unlike the teleological perspective of natural history. By contrast, the heuristic knowledge implemented in exploitive control is a result of

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[20] For background information, please refer to previous discussions in Section 2.2.2, page 27.

evolution or learning, e.g. the learning of spotting yellow colour for searching the Kodak film. The purposes/goals arising from intentions are constantly subject to change. Yet, however constantly the organisms change their tasks of active perception, the stepwise computation of active perception systems has an inherent teleological dimension.

Lastly, mechanicalism is an indispensable basis from which to explain the generation of perceptual understanding. This explanatory perspective seems to be incompatible with teleology, but in fact is not. As just discussed, certain goals are implemented *in* the heuristic knowledge of exploitive control, while certain others arise from *outside* active perception systems. The existence of goals and purposes does not affect the explanation of active perception systems from a mechanical point of view. That is, within the active perception systems that have been implemented (including their heuristic knowledge), such systems can be fully explained on grounds of mechanicalism. So these two explanatory perspectives are not incompatible. More strongly, they link mutually, given that certain goals are implemented in the form of heuristic knowledge and others arise from outside.

Broadly speaking, active perception must be understood in terms of these four dimensions together – four explanatory perspectives. Firstly, it presumes the intrinsic functionality of describing the external world. Secondly, the content of the perceptual scene must also be understood on account of the contribution of its ingredients to required tasks. Thirdly, those required tasks can be regarded as purposes (or goals) which are imposed on the stepwise computation of active perception, to see it from a teleological point of view. Lastly, the stepwise computation of active perception systems can indeed be fully explained from a mechanical point of view.

These four explanatory perspectives are not separately pursued without inter-relationship. The first explanatory perspective is presumed in the explanation of active perception, because description is intrinsic to the faculty of perception. The second explanatory perspective (pragmatism) concerns the selection of ingredients in the perceptual scene with regard to their contribution to tasks, which are the targets of the third explanatory perspective (teleology). Moreover, the stepwise computation can be fully explained from a mechanical point of view, by seeing goals either as heuristic knowledge or as externally arising intentions. Hence, the four perspectives are connected.

Given the above discussions, the previous explorations of active perception systems have established the link between those four perspectives over perceptual understanding – perception as description, contribution/consequence, purpose, and mechanism – which can be seen as internal links in a four-fold explanation, namely, the notion of perception as description, pragmatism, teleology, and mechanicalism.

7.5.3 How do Conceptual Foundations Elucidate these Links?

A conceptual foundation is understood as an *interpretation* of links of computational processes (or strategies), because it serves neither to *describe facts* nor to *characterise theoretical properties* but jumps to a higher level to *explain implementational results or theoretical properties* in more intuitive terms, as seen in the above four points of interlock. The interpretation of conceptual foundations is demonstrated as follows.

Inverse Ecological Niche The notion of inverse ecological niche, as a conceptual foundation of task-level emergence, is a conceptual foundation serving to interpret three links between external and internal processes. First, characteristics of ecological niche[21] are reflected in the exploratory and exploitative control of computational processes. Second, on the basis of the exploratory and exploitative control, active perception systems can link situated activities and internal representations. Third, also on the basis of exploratory and exploitative control, a link is forged between the environment and the computation of active percep-

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[21] For relevant background on the role of the environment, please refer to Sections 2.2.1 and 2.2.2 (pages 26 and 27).

tion systems. Notice that at both sides of each link discussed above are two knowledge sources which are relevant to the functionality of active perception systems. Thus, the notion of inverse ecological niche serves to interpret three links between different sources of process, which are relevant to the task-level emergence realised in active perception systems.

Internal Cohesion. The notion of internal cohesion also covers three links: two between the processes of different sources, and one between different requirements of emergence (namely, autonomy and adaptability).

First, in a combinatory system, processes of its sub-systems are apparently processes of different sources, as exemplified by the six sub-systems of gaze control. Were it not for the control of the combinatory system, its sub-systems would operate separately without being organised into smooth functionality. Thus, the control of the combinatory system can be seen as a link between processes of different sub-systems.

Second, different combinatory systems can be further linked into a yet more elaborate combinatory system. For example, the system of gaze control can be linked with systems of tracking, as demonstrated by human visual control. Thus, a link emerges between processes of two combinatory systems.

Third, internal cohesion relates to another type of link – a link between autonomy and adaptability – which are two requirements of emergence. Their relationship is similar to the metaphysical ideas/categories of One and Many, which serve to explain the part-whole relationship of events happening in the world. Like the realisations of One and Many in events, the respective realisations of autonomy and adaptability in the course of emergence are subject to a trade-off relation, as discussed in chapter two (see Section 2.1.3, page 25).

What is important in connection to the notion of internal cohesion is that it is a link that breaks the aforementioned trade-off relation by accomplishing *both* requirements to a high degree: each active perception system presents a high degree of adaptability to various environmental conditions and the accomplishment of required tasks is maintained satisfactorily by the mechanisms of such a system without the need for interruption (by users or designers), and without the worry of getting stuck (or even breaking-down).

In sum, the notion of internal cohesion covers three links, two between the processes of different sources, and one between different requirements of emergence.

The Factorial Conditions Computed by Quasi-functional Modules and Quasi-action Modules. The notions of factorial conditions, on the one hand, and quasi-functional modules and quasi-action modules, on the other, are conceptual foundations that work together to link perceptual systems and motor systems. Such systems can be regarded as different sources that provide processes for the stepwise computation of active perception.

As previously discussed, the basis of these two notions active perception systems (by connecting to functional specification of perceptual features and bringing about perceptual guidance of bodily actions to facilitate bodily actions) can connect to perceptual and motor systems respectively, but gather together their products – perceptual features and motor activities – between which a link is formed. These two sources (motor and perceptual systems) of processes appear to be less striking than those discussed above, but the link between motor and perceptual processes is by no means less important than others. This is because the link presented discussed here manifests the integrity between perceptual and motor systems, which in part explains the integrity of cognition – a major goal of cognitive science.

Task Identification. The notion of task identification, as a conceptual foundation, is epistemologically intriguing because it manifests three sharply contrasted perspectives for understanding the generation of perceptual understanding – mechanicalism, pragmatism and teleology. Like the contrasted categories of One and Many, these three perspectives are different sources of explanation.

The above discussions clarify a relation between scientific theories, and the implementations maintained in cognitive science and AI, on the one hand, and epistemological conceptions, on the other. That is, the unity of cognition – a perennial concern of cognitive science – can be conceived in terms of the links between knowledge sources and the conceptual foundations which elucidate such links. The contrast and cooperation between those links and conceptual foundations delineate a division of labour (in fact, cooperation) between science and philosophy. Thus, the pursuit of conceptual foundations contributes to the interdisciplinary understanding of cognition pursued in cognitive science. This division of labour between science and philosophy is described as follows.

7.5.4 Explaining the Unity of Emergent Phenomena

The Unity/Integrity of Task-level Emergence. As yet, discussions in this chapter have neither defined the term integrity/unity nor managed to explain it. Now, this topic can be pursued by building on the previously established conceptual foundations.

What does Unity/Integrity mean? In the consideration of emergent phenomena, the term 'unity' seems generally difficult to define. The notion of unity points to the integrity of variously characterised phenomena, of which emergence is a typical example. Yet, the notion of integrity itself is in question. It too requires explanation. It seems that the notion of integrity is usually used interchangeably with the notion of unity but neither of them is further analysed and explained.

The difficulty we experience in pinning down a definition of unity/integrity seems to be a matter of gap, between ontological thinking and epistemological conception. Emergent phenomena involving a certain faculty, say active perception, is thought along with the ontological dimension as a unity on account of the integrity presented by active perception systems. However, it is usually the case that there is neither sufficient scientific knowledge nor firm epistemological basis to conceive the unity of a certain faculty. This is the case, especially given the consideration that different capacities may be subject to different kinds of integration, such as the difference between the emergence of foraging behaviour displayed by ants and the emergence of flying capacity in honey bees. The former (foraging behaviour of ants) may involve cooperation between conspecifics (with the allocation of certain chemical cues by some ants and the detection of such cues by others), while the latter (flying capacity in honey bees) seems to involve reflexive iteration of wings. Despite the difference, both capacities present integrity. Perhaps, the precise definition of unity in one particular area, such as the aforementioned foraging behaviour, is hard to achieve in the beginning of study; rather, an adequate definition may need support from abundant empirical knowledge.

The unity of an area, say the task-level emergence of active perception, must be understood on grounds of its relevant conditions. As an attempt along these lines, the unity of the task-level emergence can be conceived via two points.

> **Definition of the Unity of Task-level Emergence** – The unity of a certain type of emergent phenomena can be characterised with two emphases: (1) the smooth functionality of certain emergent phenomena (2) which is brought forth by gathering together the processes relevant to these phenomena. In the context of active perception, the smooth functionality of active perception (emphasis (1)) is the timely processing of perceptual inputs in support of the survival or well-being of a particular species. The relevant processes to be gathered together (emphasis (2)) are the stepwise processes leading to the production of perceptual guidance for bodily actions, i.e. the accomplishment of required tasks.

Recall that active perception consists of various capacities, largely including various sub-capacities of gaze control and tracking. A sub-capacity (e.g. pursuit) is supported by certain task-specific utilities, as discussed in chapters three and four. The task of active perception – the production of perceptual guidance in support of bodily actions – is accomplished by certain processes that are arranged at task level. The arrangement of those processes for the required tasks is an emergent phenomenon.

Note that the above conception has both a pragmatist and a mechanicalist dimension. Point (1) is a pragmatist concern, because the processing for the demanded functionality (i.e. rapid processing and production in the light of maintaining survival or well-being) seems to fall within a pragmatist category. Point (2) is a mechanical characterisation, for the emergent processes are originally brought forth on the basis of robotic architectures, for which the relevant conceptual foundations can be seen as mechanicalist characterisation. The conception of the unity in question seems clear now. The following discussions are directed to the *explanation* of the unity conceived above.

Explaining the Unity of Task-level Emergence. The explanation of the unity of task-level emergence can be framed conceptually, on the basis of the previously built conceptual foundations. Further conceptual refinement can in principle be maintained by scholars of different disciplines, in order to conceive of the unity of emergent phenomena with significant adequacy.

The unity of the task-level emergence of active perception can be explained by highlighting the chains of support provided by the processes characterised above via points (1) and (2):

> **Explaining the Unity of Task-level Emergence.** What needs to be explained for understanding the task-level emergence of active perception is *the successful management of emergent processes at task level*, beginning from the processing of perceptual inputs to the production of perceptual guidance for the bodily actions. In a nutshell, such emergent processes are gathered together in *the course of internal cohesion*[22], the detailed processes which compose this having been fully discussed in the establishment of conceptual foundations.

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[22] Internal cohesion, according to its definition (see Section 6.4.1, page 242) is an *act* of composing various forces, which is not a single cognitive process.

As a caveat, the unity of task-level emergence is not explained by the course of internal cohesion *alone*, but by the emergent processes which are gathered together in the course of internal cohesion.

An Endeavour to Explain the Unity of Task-level Emergence. Recall that internal cohesion was previously defined (see Section 6.4.1, page 242) as the act of effectively composing all the forces involved in the *serial order* of stepwise computation, with the computational steps reflecting the various internal emphases of a task. It is worth noting that the process of internal cohesion widely involves all details relating other conceptual foundations, with regard to the relevant environmental factors and the computational processes for accomplishing particular tasks. Since all such details are gathered together in the process of internal cohesion, the course of internal cohesion can stand as the unity of the task-level emergence.

With the unity of task-level emergence being so conceived, a *how* question naturally arises: how is the unity achieved on the basis of internal cohesion? There is no single conception which can effectively explain all details, as revealed in the previous discussions on the multiplist interlock of emergence. Yet, the previously discussed conceptual foundations and the relating links between knowledge sources together would help us to reach the required resolution, without sacrificing the involving technical details, the resulting integrity of various processes in each particular implementation, or the intuitive comprehension of that integrity. Thus, the unity of task-level emergence may be explained by a *multiplist* combination of processes and conceptions.

As a reminder, among the processes centred around the course of internal cohesion is the comparison between the gathered information and the yet needed information for a required task. Note that the comparison is maintained stepwise. In each step the computation insures a relative optimised move for the next step of sensory-motor action. Such a move is by no means simple, because it is based on the explorative and exploitative control maintained by the quasi-functional modules and quasi-action modules, which manifests a certain degree of subtlety.

For example, the cooperation between the control of pursuit movements and the attentive control of saccades presents a degree of subtlety in driving sensory receptors. In particular, the control of pursuit movements (see Section 3.4.5, page 104) presents needed compensation for various errors, which arise in the unpredictable environmental conditions, in order to drive visual receptors precisely to where is really expected by the attentive control of saccades. This cooperation presents a significant degree of optimality, as manifested in the real-time maintenance of gaze on the envisaged visual features. Thus, the stepwise computation would turn out smoothly to keep an 'eye' on various visual features relevant to the required task.

The course of internal cohesion is manifested in the stepwise computation across a number of steps, by the cooperation between the control of pursuit movements and the attentive control of saccades. The course of internal cohesion is maintained by different (quasi-form) modules, but the cooperation between them manifests a subtle arrangement of control processes with a significant degree of optimality in each step, leading to the eventual accomplishment of the required tasks. The integrity/unity of task-level emergence in connection to gaze control (with regard to keeping track of target) is thus demonstrated.

Given the above example (i.e. the control of pursuit movements and the attentive control of saccades), the course of internal cohesion brings together various processes, with a significant degree of subtle arrangement in response to environmental unpredictability, which thereby leads to the accomplishment of required tasks. The unity of task-level emergence is well demonstrated by this example.

Given the above elucidation, the integrity of task-level emergence can be comprehended as the emergent processes centred around the course of internal cohesion – specifically, the emergent processes (as subject to various principles, including internal cohesion) maintained by quasi-functional modules and quasi-action modules, under explorative and exploitative control, through stepwise computation with comparison between collected information and the required tasks.

Understanding Interlock and Activeness Through the Unity of Task-Level emergence. The above explanation of the unity of task-level emergence realises (within the subject matter of active perception) Clark's request for the interlock of emergent phenomena. In addition, such an explanation of unity can also be regarded as an answer to a question raised early in the present thesis – activeness (i.e. what makes active perception work). With our conceptual foundations and relating expositions, both the questions of interlock and activeness are answered.

With the mediation of conceptual foundations between conceptual activities and those differently realised links (by different theoretical constructs and the architectures of computer/robotic implementations), the comprehension of task-level emergence and its integrity becomes relatively intuitive. The comprehension is subject to two limitations, (1) that the details of those links seem a privilege of the scientists at relevant domains and hence would very likely go beyond the reach of ordinary people's conceptual activities, and (2) that the processes of emergence from local to global activities are explainable by various principles of emergence that may be too complex to comprehend intuitively even for scientists.

The Importance of Conceptual Foundations and Links for Understanding the Unity of Cognition. The links between different knowledge sources indicate a general understanding of the unity of cognition:

> The unity of cognition in general can be achieved in terms of various conceptual links between knowledge sources. What exactly those links and knowledge sources are depends on what particular cognitive system is at issue.
>
> Such links and conceptual foundations are built for the understanding of scientific theories and computer implementations. Such an understanding cannot be reached independently by philosophical abstrac-

> tion, but conversely must be made available before the activity of philosophical abstraction is carried out.
>
> Consider the relationship between science and philosophy from the other direction. Without the above philosophical notion, the attempt to understand the unity of cognition merely with recourse to those links and conceptual foundations[23] would be too *scattered* to grasp the integrity of a particular cognitive phenomenon in question, e.g. task-level emergence of active perception. Worse, without those conceptual foundations the endeavour to understand the unity of cognition merely with recourse to scientific theories and computer implementations may even risk losing most *integrated perspectives.*
>
> Given that they mediate between science and philosophy in the process of explaining the unity of cognition, conceptual foundations stand as the pivot of understanding the unity of cognition.

This passage presents the philosophical implications of the case study carried out in the present thesis: a case study of emergent cognitive functionality by discussing the task-level emergence of active perception.

How Strong is the Need for Conceptual Foundations? – Objections and Replies. Three objections may be raised against the above philosophical implications. The first objection concerns the scope of the conceptual foundations. The second concerns the risk of begging the question. The last one is about the generality regarding the pivotal position of conceptual foundations.

First Objection and a Reply to It. The first objection concerns the scope of the conceptual foundations that are needed for explaining the unity of cognition. Discussions in this section stress the importance of certain conceptual foundations in understanding the unity of cognition – those mentioned in the four

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[23] Remember that a conceptual foundation serves to interpret a single or a number of conceptual links. Hence, simply mentioning conceptual foundations suffices to refer to conceptual foundations *and* the conceptual links of various knowledge sources.

points of interlock. Does this mean that *other* conceptual foundations discussed in previous chapters, such as the notions of process arrangement and dynamic small modules, are not needed for explaining the unity/interlock of task-level emergence?

The notion of process arrangement seems to be less important than those discussed in the four points of interlock. However, this does not mean that it is entirely redundant. Indeed, it serves as a contrast to the notion of task identification in order to delineate its (task identification) ending processes. In addition, its role is manifested in its connection to the notion of dynamic small modules, which also has its role in explaining the interlock/unity of task-level emergence. Although this notion does not seem to turn up in the discussions of interlock, it is assumed. The notion of dynamic small modules serves to explain the hierarchical organisation of sub-systems within combinatory systems. At this point, its explanatory role becomes obvious. To wit, the notion of combinatory systems is needed for explaining elaborate computational processes, i.e. the hypercycle of task-level emergence. As exemplified by the roles of these two notions (i.e. the notions of process arrangement and dynamic small modules), all notions discussed in present thesis play certain roles in the process of explaining the interlock/unity of task-level emergence.

Second Objection and Reply. Another objection may be raised – 'Conceptual foundations are only needed for the case study of empirical materials but not for philosophical investigation in general.' According to this objection, conceptual foundations are needed for understanding the unity of cognition simply because the conceptual foundations of a subject matter (such as active perception) are goals of a case study which seeks to generate a philosophical thrust by way of studying the conceptual foundations of scientific theories and computer implementations in that subject matter. In other words, conceptual foundations are needed because the author of the aforementioned case study *happen to* raise them together as the target of his research. As a consequence, taking a research target as *indispensable* without further justification would be a mistake of begging the question.

If such an objection is tenable than the pivotal position of conceptual foundations in understanding the unity of cognition would evaporate. In this vein, the study of conceptual foundations would be *optional* for understanding the unity of cognition. It might be a provocative and fruitful approach to understanding the unity of cognition, but it would not be necessary: certain yet un-explored approaches may fare equally well or even better.

In reply, the pursuit of conceptual foundations is indispensable, in the process of explaining the unity of cognition, because the mediation of conceptual foundations between the study of the subject matter at issue (active perception) and eventually gaining an understanding of the unity of active perception is *not presumed* in the research target of present thesis but is a derived result. Although conceptual foundations mediate *a priori* between science and philosophy, the research of this thesis does not presume that by deriving the conceptual foundations of the task-level emergence of active perception the research can surely achieve the unity of task-level emergence.

Specifically, the research target of the present thesis has been to study the emergent phenomena of active perception via considering certain conceptual foundations (and links between knowledge sources) in the *hope* of supporting the attempt to understand the unity of emergent phenomena. There is no presumption that the achieved conceptual foundations would *turn out successfully to mediate* between the emergent *phenomena* of the subject matter and the envisaged *unity* of this subject matter. In a nutshell, there is no presumption in the research target that the unity can be firmly achieved *simply* on the basis of such conceptual foundations. As it turns out in the process of research, conceptual foundations are *found* as actually mediating the (task-level) emergence of active perception and the unity of (task-level) emergent phenomena. The successful mediation of conceptual foundations has never been presumed in the research at the outset, hence in the above claim (that conceptual foundations are needed in the process of achieving the unity of task-level emergence) the research does not make the mistake of begging the question. The objection in question is consequently met.

Third Objection and Reply. A further objection may be raised to challenge the previous claim of the generality regarding the pivotal position of conceptual foundations. Specifically, one might claim that conceptual foundations may be simply important for the subject matter of the carried out research, but other research on different subject matter may show conceptual foundations as unimportant. The research seeking conceptual foundations of a subject may *end up with the same*: end up with what *philosophical* investigation alone can do without the engagement in the study of empirical knowledge.

As a reply, it is *logically possible*, but *scientifically unlikely*, that understanding the unity of cognition in a different subject matter needs no significant involvement of conceptual foundations and their related empirical knowledge. For research that has not yet been carried out, anything is logically possible if it is not self-contradictory. Yet, scientific research must be grounded on likelihood, in addition to logical possibility. Previous research can justify the likelihood and generality of a certain claim, although that claim is not logically necessary. Indeed, logical necessity is required for reasoning, but does not seem to be needed for the establishing the principles of *nature*.

What is demonstrated in the research carried out in the present thesis is that conceptual foundations are *highly likely* to be also *indispensable* for further researches on the unity of emergent cognitive phenomena at different subject matters. As is demonstrated in studying the task-level emergence of active perception, explaining the unity of emergent cognitive phenomena or even the unity of cognition *needs* to take account of conceptual foundations of the subject matter at issue. On the one hand, without philosophical abstraction, the attempt to gather the cognitive unity *would be* too scattered or even risk losing most ideas of integration. On the other hand, without the establishment of various links and conceptual foundations on the basis of scientific theories and computer implementations the endeavour to understand the unity of cognition *would* even lack a *beginning* for understanding the subject matter. Given the need of both sides and the previously achieved understanding that conceptual foundations mediate between both sides, the role of conceptual foundations in explaining the envisaged unity is indispensable.

7.5.5 Summary of Section 7.5

Based on the discussions in the above four sections, Section 7.5 puts forward the main contention of the present thesis, and justifies it in the context of task-level emergence of active perception. To wit, the study of conceptual foundations and the links between various knowledge sources contribute both to explaining the unity of cognition (the unity/interlock of emergent functionality) and to delineating the co-operative relationship between science and philosophy in the endeavour to explain the unity of cognitive emergent phenomena, and even the unity of cognition.

7.6 Summary

This chapter seeks to derive a philosophical basis for explaining the emergent functionality of autonomous agents, from the discussions of task-level emergence (of active perception) in previous chapters. Doing so achieves two understandings.

Regarding the first understanding, discussing the emergent functionality of autonomous agents by a case study – the task-level emergence of active perception – sharpens the focus of philosophical deliberations about emergence. Previous discussions in this chapter demonstrate that a sharpened focus helps to maintain more adequate philosophical understandings, even to diagnose certain misunderstandings.

The second understanding, as discussed in section 7.5, is the cooperative relationship between science and philosophy for explaining the unity of emergent phenomena, even explaining the unity of cognition. As a main contention of the present thesis, conceptual foundations mediate between science and philosophy to explain the unity of cognition, without sacrificing either of two important requirements of unity – the comprehensibility over all the relevant knowledge sources, on the one hand, and the integrity of all relating cognitive phenomena at a very high level of abstraction, on the other.

Chapter 8

Conclusions

The goal of this thesis has been to explain the emergence of active perception, by focusing on the processes of emergence at task level. The envisaged emergence is considered with a multiplist notion – explanatory interlock – which is articulated in the establishment of conceptual foundations.

The process of explaining task-level emergence consists of the following four steps – (1) identifying related questions and collecting theoretical backgrounds, (2) summarising the main theoretical points of active perception research and surveying its experimental results, (3) building conceptual foundations for understanding activeness, and (4) explaining the contribution of conceptual foundations to understanding the integrity of task-level emergence. Because the desired explanation relates to both scientific theories and philosophical notions, with an emphasis on their cooperation, a subgoal of the present thesis has been to demonstrate how interdisciplinary research can lead to an understanding of the integrity of emergent phenomena. This subgoal is achieved in the creation of conceptual foundations, which offer the possibilities of further conceptual activities across disciplines.

8.1 Questions and Background Knowledge

8.1.1 Questions

There are two aspects to an informative account of active perception – scientific understanding and philosophical explanation. On the scientific side, the present thesis emphasises the need for an explanation of *how* active perception systems accomplish their tasks. In particular, two important properties of active perception have not been identified in previous researches – that active perception systems accomplish their tasks through emergence, as opposed to full determination by design, and that the course of emergence mostly takes place at the task level, i.e. during run-time, as opposed to learning.

On the philosophical side, this thesis raised the need to go beyond the distinction of *internal* and *external* processes of emergence. As an alternative to this distinction, discussions in the present thesis focus on gaining an explanation of emergence by answering the question of *why* active perception systems in general can accomplish their tasks in the course of emergence.

To address these *how* and *why* questions, discussions in the present thesis raise a notion – activeness – which concerns *what* makes active perception work. As a consequence, efforts toward building conceptual foundations can be seen as contributing to an understanding of activeness.

8.1.2 Background Knowledge

The background knowledge mainly comprises conceptual analyses and the various design strategies of behaviour-based systems.

Conceptual Analyses. Certain important conceptions relevant to the explanation of emergence and active perception have been discussed. Firstly, the conception of *active* perception is defined, using a combination of requirements, with emphases on the movements maintained for receiving needed perceptual inputs and the iterative computational processes over the needed information for the required tasks.

Secondly, the notion of autonomy is analysed in relation to the notion of adaptability. A central component of autonomy is self-maintenance in the light of high adaptability to environmental circumstances.

Furthermore, the notion of emergence is defined, beyond the local-global distinction, as a negative concept of pre-determination, which is defined in terms of *pre-categorised* data/descriptions and inference mechanisms.

Lastly, the conception of *internal representations* are analysed into five types, in order to identify clearly the various types of representations implemented in active perception systems. One advantage of this analysis is the understanding it provides of the integration of representations across types.

Design Strategies of Behaviour-based Systems. For the purpose of distinguishing between various design strategies of active perception systems, two issues are discussed. The first is the role of Brooks' subsumption architectures in the behaviour-based systems and the advance of internal control in an account of action modules which is exemplified by Maes' control of energy spreading. The second issue is the relationship between exploration and exploitation, two common control strategies. Exploration emphasises robots' directions in different parts of the environment, while exploitation emphasises the planning of robots' actions on the basis of heuristics of external events and various mechanisms of code arrangement, such as energy spreading (Maes (1990b)) and the differential equations maintained by dynamical systems.

8.2 Theories and Implementations of Active Perception

The characteristics of active perception were discussed in chapters three and four, with regard to the general paradigm and the characteristics of various active perception implementations, in particular including systems of gaze control, tracking, and run-time planning. Identifying the *theories* of active perception is an indispensable part of carrying out a case study on active perception. Yet, theories only provide the paradigm of active perception, without explaining what makes active perception work, i.e. activeness. It is consequently also necessary to go a step further in explaining the *mechanisms* of successful implementations. Discussions in chapters three and four revealed that explaining such mechanisms provide firm grounds for further explanations of activeness via conceptual foundations or philosophical notions.

8.2.1 The AB and BC Perspectives on Active Perception

In order to explain activeness, the discussions in chapter three characterised the paradigm of active perception research by the distinction of the AB and the BC perspectives of active perception. These two perspectives have certain commonalities but possess significantly different emphases.

A commonality between these two perspectives is the importance of task-specific facilities and observers' movements for perceptual computation, in order to gain access to more relevant perceptual features.

The AB perspective largely emphasises the importance of exploration, as opposed to exploitation, by deriving unknown parameters from the computation of known parameters (advocated by Aloimonos *et al.* (1988)) (i.e. from the explorative activities themselves) or by building external frames (as in Ballard (1991)). By contrast, the BC perspective emphasises explorative control, which consists of explanatory activities (stated by Bajcsy 1988) and environmental cues (Churchland *et al.* 1994).

8.2.2 Explaining the Mechanisms of Implementations

A significant amount of effort in the present thesis has been devoted to analysing current implementations of active perception. The most notable implementations under examination are as follows:

- **Gaze Control** – attentive control of saccades, the control of pursuit movements;
- **Tracking** – Snake, dynamical Kalman filter (including Dickmanns' car);

- **Run-time Planning of Visual Paths** – Adept; and
- **Active Perception beyond Visual Modality** – Roberts' system of active haptic perception, Allen and Bajcsy's robot of visual-tactile integration, and Scheier and Lambrinos' robot of active categorisation.

8.3 Building Conceptual Foundations for Understanding Task-level Emergence

Efforts to build conceptual foundations are presented in chapters five and six, which respectively address two dimensions of task-level emergence. Regarding the first dimension, chapter five serves to characterise the explorative and exploitative control of active perception systems in the form of conceptual foundations. Regarding the second dimension, chapter six strives to explain task-level emergence, specifically to account for why local activities lead to emergent phenomena – the accomplishment of required tasks.

8.3.1 Explorative and Exploitative Control of Task-level Emergence

Analysis of active perception makes a distinction between **task identification** and **process arrangement**. The former concerns the initiation of appropriate processes, while the latter regards the continuation of computation leading to the accomplishment of required tasks.

Tasks Arising from Intentions or Constant Interests. Arguments begin with the identification of tasks, by showing that tasks arise from *outside* the active perception systems, mainly in two ways.

In the first of these, tasks arise from intentions of real organisms but are identified within active perception systems via representations, such as weights in attentive control of saccades. This kind of task identification can be implemented by designers' intention and robots' internal representations (specifically, templates of environmental circumstances). In the second way, tasks arise from constant interests, as manifested in reflex activities of prey in response to the perceptual cues of predators approaching, which can be implemented through the exploitation (heuristic knowledge) of environmental factors.

To consider the relationship between exploration and exploitation, discussions highlight the need for exploitative control (implemented by cues and templates of environmental circumstances), although gaze control and tracking would unavoidably involve a significant degree of explorative control.

Process Arrangement. The explanations of process arrangement involved three steps. First, attention is directed to the nature of active perception systems, as discussed in the notions of *factorial conditions* and *quasi-functional modules and quasi-action modules.* Second, discussions characterise process arrangement by certain requirements, as manifested in the notion of *dynamic small modules.* Third, it is argued that dynamic small modules are exclusively realised by quasi-functional modules and quasi-action modules.

Factorial Conditions. Discussions made it clear that active perception systems do not identify tasks explicitly. This point is addressed in the notion of *factorial conditions.* The notion of 'factorial conditions' is introduced to mean the perceptual factors caught through sensors and transformed via numerical computation, such as the visual contours dealt with under a visual filter (e.g. Kalman filter) and the features fetched in the attentive mechanism of saccades. Thus, factorial conditions are not functional descriptions, but numerical transformations (through various perceptual mechanisms) of the perceptual features of the external world. Because perceptual inputs are represented in the form of factorial conditions, the implementation of active perception systems identifies tasks implicitly.

Quasi-functional Modules and Quasi-action Modules. The present thesis argued that the basic components of active perception systems are neither functional nor competence modules, although such components do manage to compute certain functional descriptions and indeed give rise to guidance of bodily actions. Thus, such components were characterised in terms of *quasi-functional modules* and *quasi-action modules.*

Dynamic Small Modules. The architectures of active perception systems are discussed using the notion of *dynamic small modules*, which basically consists of three points – that successful process arrangement is based on small-size (simple) modules which constitute operation-specialist systems, that the elaboration of active perception systems must impose hierarchical or heterarchical orders on operation-specialist systems, and that the arbitration between those modules must be sufficiently dynamic. This notion is further specified by the following two characteristics: (a) dynamic small modules should be capable of maintaining stepwise and iterative processing gradually to address the external enquiries (i.e. perceptual tasks) in the real environmental conditions; (b) dynamic small modules must be capable of grasping and keeping track of fast-changing shapes accurately.

Dynamic Small Modules Must be Exclusively Realised by Quasi-functional Modules and Quasi-action Modules. This suggestion marks a considerable difference between active perception systems and other behaviour-based systems. As has been demonstrated, the reasoning behind this suggestion is grounded on the previously derived characteristics of Marrian theory of vision, active perception systems, and other behaviour-based systems, such as Brooks' subsumption architecture, Steels' exploitative control, and Maes's system of energy spreading. In particular, the reasoning takes advantage of four types of exploitative control provided by quasi-functional modules and quasi-action modules: judgement under uncertainty, using templates, using dynamical systems, and planning of actions.

After this suggestion has been defended and justified, the characterisation of active perception is completed. Later parts of this thesis aimed to explain the principles of task-level emergence.

8.3.2 Understanding Emergence

The understanding of task-level emergence is based on four principles extracted from four models of life origin, and, in addition, a novel notion – **internal cohesion** – which particularly characterises the formation of serial orders in the task-level emergence of active perception.

Extracting Principles of Life Origin and Thereby Establishing Principles of Task-level Emergence. The first model is Rosen's (M,R)-system, which reveals two points for understanding task-level emergence. First, while the **fundamental structures** of life origin are biochemical structures, those of active perception may refer to the stepwise computation that brings forth the guidance of bodily actions. Second, the task-level emergence grows from **baseline** to **elaborate** patterns of emergent phenomena, specifically from several small operation-specialist systems to a combinatory system, as exemplified by gaze control and Dickmanns' car. Corresponding to the baseline patterns is the second model, Kauffman's autocatalytic network, which reveals the minimum requirement of the stepwise computation of active perception, namely, the stable and continuing processing within one *single step* of computation. Corresponding to the elaborate patterns is the third model – Eigen's model of hypercycle, which reveals that the stepwise computation of a combinatory system is based on mutual support between several sub-systems.

Common to both baseline and elaborate patterns is Maturana and Varela's notion of autopoietic unity, which hints at a principle of task-level emergence – that the basic computational cycle of task-level emergence consists in the comparison between collected and still needed information, in order to *insure* that the previous outcome really *contributes to the required tasks.* This is in part a mechanicalist and in part a *pragmatist* characterisation of emergence.

Apart from the above four principles, the following notion is very important.

Internal Cohesion. The notion of internal cohesion denoted the act of neatly arranging *serial* steps of computation by transforming or scheduling the forces taking part in a particular system, with such forces manifesting various internal *emphases* of a task (in the derivation of perceptual guidance). This notion applies to stepwise computation in both a single simple system and a combinatory system. This notion highlighted a remarkable point about emergence, that the internal control of active perception systems is not explained purely by the relationship between internal representations, but is also driven by various aspects of the task corresponding to environmental conditions. That is, active perception systems stepwise refer to perceptual *inputs* from various environmental circumstances and then strive to *put together relevant computational processes* that generate the guidance for the required task.

The notion of internal cohesion has an impact on the link between environment and the internal processes, as demonstrated below in the relationship between environment and the stepwise computation of task-level emergence.

8.3.3 Understanding the Impact of Environment on the Explorative and Exploitative Control

The environment is seen in autonomous agent research as the indispensable mediator of emergent functionality. In addition to this understanding, the last section of chapter six provides a novel viewpoint to account for the relationship between the environment, on the one hand, and the explorative and exploitative control of behaviour-based systems, on the other. This point of view is captured in the notion of **inverse ecological niche**, which states that for a certain organism the mechanisms of its active perception system reflect various characteristics of this organism's ecological niche. In addition, the stepwise computation of the needed information for the required tasks manifests the organism's 'strategy' of carrying out those tasks in its ecological niche.

8.4 Links, Conceptual Foundations, and Integrity of Task-level Emergence

The previously built conceptual foundations contribute to the conceptual understanding of various aspects of task-level emergence. Chapter seven shows that such conceptual foundations can be integrated by several philosophical notions – multiplist interlock of emergence phenomena, various aspects of cognition, and links between knowledge sources.

The Notion of Interlock. The first notion is **multiplist interlock of emergent phenomena**. This notion originates in Clark's conception of explanatory interlock over the trinity of emergence, and is further supported by the **multiplism** which conforms to Clark's conception of explanatory trinity: the various aspects of cognition can be seen as multiple emergent phenomena, which arose in response to a variety of evolutionary problems and turn out to be characterised at different levels of description.

Links between Different Knowledge Sources. The multiplism introduced would risk ending up as mere eclecticism, unless the multiple interlock of emergent phenomena can be successfully explained. The interlock of emergence is considered by Clark as a *target* of explanation between various aspects of cognition, without being further accounted for. The present thesis established an interlock for a specific subject matter – the task-level emergence of active perception – via several *links*, as seen in four dimensions of integration over different sources of knowledge.

1. integration of external and internal processes in the determination of task-level emergence;
2. explaining global behaviour on the basis of various principles;
3. linking perceptual features and motor actions; and
4. linking different accounts which explain the generation of perceptual understanding – perception as recovery/description, pragmatism, teleology, and mechanicalism.

Each instance of integration in one dimension of integration, e.g. the integration between situatedness and representations in the first dimension (see Section 7.5.2, page 306), constitutes a link between different knowledge sources. Although a demonstration of integration between different knowledge sources is common to all links, different links may be realised in different ways. As a rule of thumb, for different aspects of cognition each aspect (of cognitive phenomena) may have its pertinent type of linkage between different knowledge sources. Different types of linkage are realised in accordance with different system architectures and different theoretical descriptions. Although those differently realised links may be difficult to conceive of, the conceptual foundations developed in the present thesis serve to explain such links as intuitively as possible.

The links demonstrated in the above four dimensions of integration can serve to explain the notion of multiple interlock. On grounds of the already built conceptual foundations, the integrity of task-level emergence can be comprehended as the emergent processes centred around the process of internal cohesion: specifically, the emergent processes (as subject to various principles, including internal cohesion) maintained by the quasi-functional modules and quasi-action modules of a simple specialist or a combinatory system, through stepwise computation with comparison between collected information and the required tasks.

Although understanding the links between different knowledge sources of task-level emergence may be difficult for philosophers, ordinary people and even the scientists of different areas, those conceptual foundations are intuitive. Such conceptual foundations offer possibilities of further interdisciplinary deliberations on the integrity/unity of emergent cognitive phenomena.

A Demonstration of Cooperation between Science and Philosophy. Based on the discussions of links, this chapter explains the unity of cognition (the unity/interlock of emergent functionality) and delineate the co-operative relationship between science and philosophy in the endeavour of explaining the integrity/unity of cognitive emergent phenomena.

8.5 Future Research

Certain extensions of research on active perception can be pursued. Firstly, the biological systems of active perception are largely unknown (except for the short work by Churchland *et al.* (1994)). Although robotic implementation is taking account of some biological systems, it is likely that evolution implements active perception in a way different from robotic *design*. It is likely that the role of the environment will consequently become more clearly explained.

Secondly, the conception of active perception can be extended to systems that maintain selection over perceptual inputs on grounds of attention. It will be intriguing to see how attention interacts with explorative and exploitative control.

Thirdly, particularly for philosophers, the definitions of emergence and predetermination can be refined, especially considering the integration between task-level emergence and the emergence at other levels – the emergence of (real and artificial) life in evolution, (embryogenetic and psychological) development, and constructive learning. If there can be a common definition of (artificial and real) life (as has been debated in ALife study), can there be a common definition of emergence? In addition, for explanations of different emergent phenomena, a further question is worthy of deliberation: does the integrity of different emergent phenomena, e.g. evolution vs. development, conform to the same groups of principles?

Lastly, the conceptual sophistication imposed on the conceptual foundations of a subject matter, such as the subjects mentioned in the three points above, may provoke interesting deliberations on the subject matter, at least over the definition and explanation of the unity/integrity of that subject matter. As a further example, the generation of perceptual understanding has been studied on grounds of four explanatory perspectives – the perceptual understanding as description, pragmatism, teleology, and mechanicalism – which together address the broad relatedness involved in the unity of perception. Although these are likely to be complicated, such deliberations may result in a more profound understanding of principles of nature than that which arises when philosophy and science are pursued separately.

8.6 Conclusion

Active perception research introduces a new paradigm for understanding perception, but the distinctive type of emergence underlying active perception – task-level emergence – has received little attention in recent studies of emergence. This thesis has presented a set of conceptual foundations for explaining the task-level emergence of active perception. Such conceptual foundations elucidate various links to merge different aspects of emergent phenomena in connection with active perception. By building those conceptual foundations for a particular subject matter – active perception – the present thesis has demonstrated a cooperation between science and philosophy for the purpose of understanding the unity of emergent cognitive phenomena.

Appendix A

Two Implementations Using Exploitative Control

A.1 Steels' Implementation: Various Properties of Wave

The task of Steels' implementation is to establish a mobile robot which can explore the environment by wandering around it, detect moving food sources of different types, exploit internal representations by building a dynamic map of those moving food sources, and find a route to catch the food. This implementation provides a prototype that manifests the emergent foraging behaviour of low organisms. Of course, certain primitive adaptability for the foraging behaviour must be derived from the robotic implementation, specifically from a limited number of simple reactive and diffusive activities which are detected in the biochemical nature of low organisms. Steels conceives of such activities in terms of the activities performed by autonomous agents, in the context of *multi-agent automata*, which comprises sensor, effector, and a simple instruction set (Steels calls it the 'script') that serves to control the activities of an agent by specifying how it should respond to a message received from other agents.

Steels implements two groups of representations, one representing the immediate conditions of the external world, the other serving as a memory of external conditions. As a simplification, the targets – food sources – are implemented by different *light* sources. He does not attempt to reconstruct the external world, but only records what the light sensors bring to the internal states. The robot acts to catch the food of a certain type by exploiting internal representations, and it does so after it detects the food of that type in the course of its 'exploratory' activities. Note that when the robot derives a food target (of a certain type) at a certain location and manages to arrive there, the food source may have moved elsewhere (be eaten or run away!). There must be a comparison, hence, between two groups of representations, in order to update the recorded representations/knowledge. It may be contended that working out a route in the map (memory) is less efficient than direct reaction. However, the manipulation on a map is more effective (than direct reaction) with regard to the planning of a route which can avoid the recorded obstacles and lead to food of a certain desired type. In a complicated case, when the robot is tightly surrounded by obstacles, it needs to remove certain obstacles on its way to the target. The robot can even record a corner and later avoid passing by that location. It is evident, from human experiences, that the adoption of an internal map would make foraging (or shopping in the town) more effective than reactive behaviour which needs to work out a route from scratch every time.

The internal representations, by which the robot records the external world, are largely analogical but with some markers which take note of certain specifically identified objects. The representations of a certain group, both the immediate representations of the external world and the memory, are allocated in the form of a grid. Such an allocation (the combination of analogical representations and specific markers) capture, to a high extent, the common nature of a map, be it a geological map printed on paper or a mental map roughly maintained by attention. Accordingly, the external world and internal memory are not represented by syntax and specific contents of lexicons, but by the analogical (typically, spatio-temporal) inter-relations between different parts of the grid. Thus, the internal states of Steels' implementation consist of non-symbolic representations but still represent the external world, even with memory. Note that the immediate representations and the memory should not be divided according to the dichotomy of input data and a common storage which represents the information of the external world, unlike the symbolic approach in traditional AI.

Rather, either of them forms a single group of internal representations. Different groups are allocated in separate grids, which are subject to comparison, on the basis of their respective spatio-temporal inter-relations.

Steels' Exploitation of Internal Representations. A further difference between Steels' approach to internal representations and the symbolic representations in traditional AI, is the strategy of *search* across the internal representations. Of course, the search in Steels' implementation cannot consist in the matching across syntactic representations. It must take advantage of the spatio-temporal inter-relations. Steels identifies the search with two activities. One is to find out the location of the target food type from the standpoint of the current position, while the other is to find a route to that location.

Steels identifies the food sources of different types with lightsources that respond differently to longitudinal waves with different wave-length. Such a design relies on temporal inter-relations, because the waves of different wave-length can be identified (from the standpoint of a specific food source[1]) by the difference in wave frequency between different wave types. A wave with a certain length, which stands for a certain food type, is issued from the current position of the foraging organism. The wave can proceed everywhere in the memory grid, and consequently the location of the target food source can be identified straightforwardly, on the basis of different wave frequencies.

Later, what is needed is to find a route from the current position of the foraging organism to the target food source. This is done, in Steels' implementation, by the emanation of a gradient field which propagates over the grid. A built-in sensor serves to trace the gradient field from the current position, which probes from lowest to highest gradient, where the target food source is located. Thus, the route toward the target food source is identified, if that food source is not hindered severely by obstacles.[2]

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[1] Steels sees the food source as an agent, as opposed to the agent of the current position. Hence, the term 'standpoint' is not inappropriate.

[2] If the food source is unfortunately surrounded by obstacles, the robot needs to remove those obstacles directly on the way toward the target, be it can trace the gradient field emanated

Emergence. The task, as a global behaviour, is accomplished without global representations of locations and actions. Rather, it is achieved on the basis of certain simple local operations, namely the waves of different wave-length, diffusion of wave, and the decay of the gradient field. Although the wave and gradient field can traverse across the whole memory grid, the identification of the target food source and that of the route toward it are not global behaviours. This is because the implementation needs no common geographical representations of locations and routes. The identification of food source and route, as a global behaviour, is facilitated by the analogical (spatio-temporal) inter-relations maintained by those operations. Such operations can be seen as action primitives working in the *internal* models, and the derivation of global behaviour is based on local activities. Like the behaviour-oriented agents approach with regard to the activities in the environment, Steels' approach also supports emergence on grounds of local activities.

Note that the above local activities are *reactive* activities, despite their being reactive on the basis of internal representations and internal actions. Agent behaviour may well be reactive not only between organism-environment but also between internal agents and internal representations. Apart from reactive local interactions it is hard to find any machinery of emergence in Steels (1990). The notion of emergence via exploitation, though, can be further elaborated, as we will see in Maes (1990b). She implements a network of differently weighted (explicit) goals, over which action selection is determined by the change of weights.

A.2 Maes' Implementation: Energy Spreading

The architectures of Maes (1991), which adopts the control of energy spreading, is described below.

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from the target food source. In Steels' implementation, the facility of the required removal is demonstrated. The obstacles to be removed are exactly those encountered in the course of tracing the gradient field toward higher gradient.

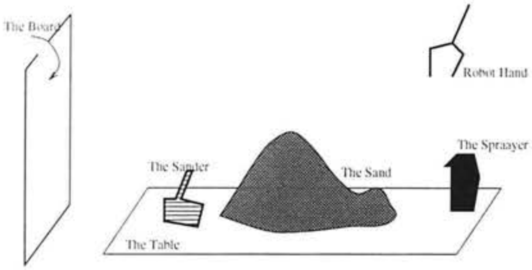

Figure A.1: **An Example of Action Modules, Implemented by Maes (1990b).** The goals and pre-conditions are represented explicitly, but there is no explicit specification as to how the robot can manage to take right actions. In the following is an example of internal representations – the action module `PICK-UP-SANDER`:

```
PICK-UP-SANDER
   : action ...
   : condition-list '(hand-empty, sander-on-table)
   : add-list '(sander-in-hand)
   : delete-list '(hand-empty, sander-on-table)
   : activation-level 18.678
```

(an example in Maes (1990b), figure 1, p. 53; the above figure is not in Maes (1990b) but is drawn by the present author according to Maes' descriptions of her own implementation.)

The Architecture of Planning. Maes (1990b) implements a robot to carry out a *task*: pick up the *sander* in order to take the sand from the table surface to a board. The task is complicated by a *sprayer*, which is left beside the sander. As an interpretation, an action (e.g. the action specified in `PICK-UP-SANDER`) can be seen as a *global goal* of this task (i.e. to achieve the state of sand-on-board). Accordingly, a *subgoal* of this task can be taken as the achievement of one description in the condition-list of `PICK-UP-SANDER`, e.g. the achievement of '`hand-empty`'.

Before it can accomplish the task, the robot must ensure that its hand is holding the sander. Otherwise, the robot needs to manage to put down whatever is already grasped in the hand (in this toy model[3], the only alternative is the sprayer), and alternatively find the sander and pick it up. As is demonstrated by Maes' implementation (see figure A.1), the network of goals, specifically, consists of:

Action Modules. A set of action modules[4], such as `PICK-UP-SANDER`, is characterised in language-like representations.

The Internal Representations of a Certain Module. A particular action module, in turn, consists of (1) an action to take, (2) a list of (conjunctive) pre-conditions, (3) a list of (conjunctive) descriptions to be added, (4) a list of (conjunctive) descriptions to be deleted, and (5) a threshold of *activation energy* for this in particular module. Any goal, be it a global goal or subgoal, must take the form of action; by contrast, states of the external world should take the form of description. The latter four elements constitute the condition of a module $x = (c_x, a_x d_x, \alpha_x)$, with two kinds of output – (a) activation energy distributed between modules, and (2) the initiation of the specified action.

---

[3] Maes (1990b) states that more elements, goals or descriptions, can be added into her implementation, and consequently extend the repertoire of the robot's capabilities.

[4] Notice the nature of such action modules, as opposed to the functional modules proposed in Fodor (1983). Such action modules are named by Maes (1990b) (1991) as 'competent modules'. Because the outputs of such modules are motor actions (by the implemented robot), we name the competence modules as *action modules*.

Activation Energy. The actions of particular action modules (in this context, we simply call them 'modules') are controlled by a quantity called activation energy. When activation energy flows, a module receives (i.e. is assigned), or has removed, a certain amount of activation energy. Such activation energy can be added up accumulatively, or be gradually reduced. The specified action of a module will be initiated, when (and only when) the activation energy distributed to it grows up to, or beyond, the specified threshold.

The flow of activation energy, under the design of Maes (1991), is initiated in three ways – observation, goal, and coherency. As a conceptual foundation of her design, the reasons for these three ways of energy flow can be understood[5] as follows. First, an observation of a robot, presumably, must change its internal states, for any design of mobile robot with internal representations. Second, the achievement of a general goal may amplify the activation levels of those processes that contribute to it, and conversely lessen the activation levels of those inhibit it. Such a strategy of design can be understood analogically in terms of politics, that a winner in an election campaign rewards his supporters and simultaneously manages to suppress the possible influence of the leaders of the antagonists. Last, a design must strive to maintain the coherency of goals; otherwise the performance might be awkward. For example, if the activation level of the action module `PICK-UP-SANDER` is not reduced immediately after its action being initiated, it is very likely that the network will request, shortly later, a second initiation of that action module, which requires the robot to pursue '`hand-empty`' as a subgoal. Then, the robot manages to initiate `PUT-DOWN-SANDER`, which soon makes the previously achieved global goal undone. The robot may consequently never actually succeed in achieving a required global goal (picking up the sander), and in turn it would never achieve the task. Therefore, the coherency between goals must be maintained.

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[5] When Maes (1990b) describes the technical details of those three ways of energy flow (p. 54), she does not explain the reasons for her design.

Activation by Observing the Current Situation. An observation (through the sensors of the implemented robot) of the current situation (of the external world) comprises a set of descriptions. The effect of an observation is the spreading of (a certain amount of) activation energy toward every module with one of those descriptions in its condition list, e.g. from the observation of a sander on the table and the empty hand to the module `PICK-UP-SANDER`. Thus, observation initiates the flow of activation energy in the network.

Activation and Inhibition Maintained by the Achievement of a Global Goal. Once a global goal, say the action of '`pick-up-sander`', is achieved, the action modules that support '`pick-up-sander`' must make available its pre-conditions (i.e. '`hand-empty`' and '`sander-on-table`') in their respective add-lists. The activation levels of those supporting action modules, under Maes' design, will be increased, in the further activities of planning in the network. By contrast, the activation levels will be reduced for those action modules that will undo the global goal at issue, i.e. those action modules (e.g. `PICK-UP-SPRAYER`) with a description in delete-lists ('`hand-empty`') that is also a pre-condition of the global goal '`pick-up-sander`'. As an intuitive interpretation of Maes' design, the promotion of those supporting modules together with the suppression of those conflict modules is a strategy for *facilitating* the quick initiation of the same global goal (i.e. the action of '`pick-up-sander`'). The quick initiation of that global goal can be foreseen, straightforwardly, because the later processing would be more likely to select its supporting action modules but less likely to select the action modules that undo it.

Maes suggests that some, or all, action modules, which once are initiated, can be habituated. Such a suggestion can be understood intuitively, as we may realise, that the implemented robot may consequently become more interested in trying *new* controls, by arranging new action sequences to accomplish the required task.

Three Types of Links. In the light of maintaining the mutual *coherency* between different action modules, the activation energy flows (by design) between those modules through three types of pre-specified links.

(1) *Successor Link from Module x to Module y*: if an element of module x's add list is also an element of module y's condition list, the activation of the module x will cause the distribution of activation energy from x to y. That is, the module x *spreads* activation energy forward to module y. For example, there is a successor link (but not the converse) from `PICK-UP-SANDER` to `PUT-SAND-ON-BOARD`. The arrival of activation energy (of a certain amount) in module y will not necessarily be sufficient to initiate the action of its specifies, but will be added on the top of its previous activation level. Note that a successor has a single-way direction from a specific module to another.

(2) *Predecessor Link*: For every successor link from x to y, there exists another link, called predecessor link. If y is not yet executable (i.e. when its activation energy is lower than its threshold), y sends a fraction of its activation energy backward to x. Such a direction of energy distribution, according to Maes' exposition, is to make y facilitate itself by making easier the activation of x, its predecessor.

As a criticism, such a route of distribution, designed by Maes, seems to be counter-intuitive, because it confuses us in our understanding of two other directions of reasoning. First, according to *abductive* reasoning, the execution of y would also increase the activation level of x. The module x, then, will be increasingly more likely to activate, no matter whether y is excutable or not. This becomes a difficulty of Maes' design. Second, if certain pre-conditions of y's are denied, and hence y becomes not executable, x (as a predecessor of y) should consequently become not executable. There is no reason, then, to make easier the activation of x (by increasing the activation energy of x).

A reasonable design of the predecessor link, as is demonstrated in these two types of reasoning (abduction and converse deduction), should be corrected, according to the ways of energy distribution we suggest. However, despite the above criticism, the notion of a backward link from y to x is understandable, given that such a link can realise the above two types of reasoning.

(3) *Conflicted Link* from x to y: if a description in the condition list of x also appears in the delete list of y, i.e. if the action of y will *undo* x (and consequently undo the action-to-be-carried-out specified in the action module x), the activation of y should lead to the *inhibition* of x (i.e. the reduction of x's level of activation energy). For example, the action of the action module `PICK-UP-SANDER` (y) inhibits a *later* activation of itself (x), because the description 'hand-empty' appears in the delete-list of y but also appears in the condition-list of the x (the later action).

Competition between Action Modules. Within the network, the activation levels of action modules are subject to competition: the strongest one is selected, by carrying out its specified action. On the occasion that two action modules turn out to be equally strong in their activation levels, according to Maes' design, one of them is selected randomly. With such a design, the network will single out a global goal smoothly, if the process is not locked by a loop. Loops are possible to happen, however, for the system in question does not maintain a history of its past behaviour. Maes foresees this problem, and suggests two solutions. One is simply to introduce a certain degree of randomness in the system. The other is to set-up another network to monitor possible loops in the first network, and take action when loops are detected. Thus, the network can go smoothly to single out actions, according to its task, the relating goals, and subgoals.

Retry. When the robot system in question fails to take any action, all the thresholds will be (automatically) lowered by 10%. They will not be reset to their respective initial values until the specified action of one action module is taken.

Hand-setting the Relative Influences of Goals vs. Internal States. Maes designs two *global parameters*, γ and ϕ (among others), for weighting the importance of either goals or states, as we have seen previously that the flow of activation energy (in the network) may be initiated by either an observation or a goal. These two parameters must be hand-set before the robot system begins to run in the given environment. The amount of their values has far-reaching impact on the following three types of trade-off relations.

Trade-off Relations. Three trade-off relations can be inferred as follows from those two parameters, in consideration of their respective impact on the process of emergence. Such an impact can be seen as an arrangement over the spreading of the activation-energy ratio between γ and ϕ (Maes 1990b, p. 56), e.g. between goal and current states.

- *Goal-orientated vs. Opportunistic.*

  As Maes (1990b) points out, the reactive activities become more opportunistic, when the ratio of ϕ over γ increases, i.e. the activation-energy becomes being determined more by current situations than by goals.[6]

  Notice that the situated agent researches are not exclusively grounded by Brooks' stance (see Brooks (1991a)) – that representations are unnecessary in robotic implementation. According to such a stance, no situated activities would be pushed forward by learning or the exploitation of internal representations and goals.

- *On-going plans vs. Adaptivity.*

  Another trade-off relation can be maintained between the influences of ϕ and *activated* γ, on the one hand, and the average level of activation within the network (named as π), on the other. That is, the values of both ϕ and activated γ may fall onto a spectrum, from very small to very large, in comparison with the mean value π of activation energy. For example, when ϕ and activated γ are set very small, the agent behaviour will be put under the direct influence of the global goal and hence be adhesive to the on-going plan. As a consequence, the agent is only slightly influenced/biased

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[6] Maes names this difference in terms of a contrast between 'situation-orientedness' and 'goal-orientedness' (Maes 1990b, p. 61).

by environmental conditions and the opportunistically achieved subgoals. The same effect is produced, in Maes (1990b), by reducing the *threshold* of whole system. The following discussions are equally applicable to either way of value decrease (i.e. either threshold, on the one hand, or ϕ-and-*activated*-γ, on the other). To economising on space, we only discuss the decrease of ϕ and activated γ.

A system sticking to an already carried plan, is presumably hard ('reluctant') to change adaptively and opportunistically. Such a property of perseverance is implemented by reducing the influence of ϕ (the activation spreading of encountered situations) and the activated γ (the activation spreading of activated subgoals). As is demonstrated by Maes (1990b), after a system has carried out a plan on the basis of a global goal, the system does not shift to a better global goal and its relating plan. Note that an implicit assumption of a system is that it can have more than one global goal. The system tends to stick to an old plan, even when an alternative global goal with a shorter path (i.e. with less *required* modules) is added to the system. The system is found to continue working on the previously attached global goal. In other words, the environmental conditions and the opportunistically achieved subgoals do not seem to take effect in the process of determining a new plan. This is an effect of perseverance. Here, we can understand this point intuitively by an example – with a written examination. Once a student makes a plan of answering questions and thereby starts to consider how to answer a particular question, he will be very unlikely to shift to another one, even though serious difficulties of answering the present question are encountered and the newly detected question seems to be much easier. The student, in this example, is adhering to a certain plan of question answering, and is not flexible in arranging a new plan adaptively and opportunistically.

- *Thoughtfulness vs. Rashness into Local Minimum in the Energy Landscape.*

  It is not necessarily good to favour the adaptive environmental conditions and opportunistically achieved subgoals over a certain global goal and a

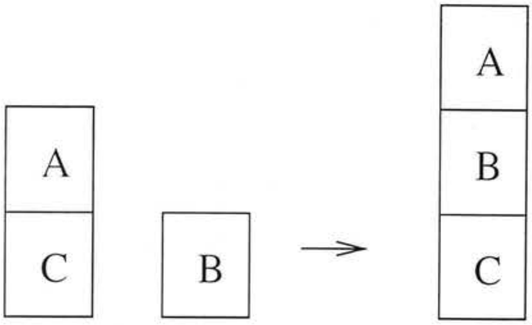

Figure A.2: **An Example of Conflict Goals.** The initial observed situation is $S(0) = (clear-a, clear-b, a-on-c)$. The goals are $G(0) = (a-on-b, b-on-c)$. As is determined by the nature of the required task, the latter item $b - on - c$ should be achieved *first*. That is, once $a - on - c$ is achieved, it becomes more difficult to achieve $b - on - c$. However, the system, instead, is very tempted to achieve the former goal $a - on - b$ immediately, because the pre-conditions of this goal are readily matched in the present situation. The problem is, as is indicated by the nature of this required task, that achieving this goal $(a - on - b)$ conflicts with the achievement of the global goal $G(o)$. (Re-drawn with configuration from Maes (1990b), p. 64.)

fixed plan. On the contrary, such a preference may deadlock the system in a local minimum of activation energy. In the case where a subgoal conflicts with a global goal, the system risks going to go rashly toward a limited amount of subgoals in the near future, but consequently straying farther away from the global goal (see figure A.2).

To escape from such a deadlock situation, the system must be more 'thoughtful', in the sense of being less inclined to take action and more likely to travel a wider range of processes. This can be done, as Maes indicates, by increasing the threshold of activation level, which makes the activation of a single module less easy and consequently makes the spreading of activation energy wider in the range of on-going processes. As a consequence, the system would not go rashly into, say, the achievement of the tempting subgoal $a - on - b$, because a inhibition link of $b - on - c$ suffices to prevent the immediate activation of $a - on - b$. As a particular method of preventing inappropriate activation, $not(a - on - b)$ (meaning that a is not on b) can be put as a pre-condition, among others, of the subgoals $b - on - c$. If the threshold is set significantly high, when the system begins to spread activation energy to the modules $a - on - b$ and $b - on - c$, neither of these two modules would collect enough activation-energy. The advantage of the inhibition link is that the threshold of $a - on - b$ is raised higher. As a consequence, the threshold of $b - on - c$ would be reached *earlier* than that of $a - on - b$, which is a satisfactory control.

Thoughtful and Pragmatist Flow Toward the Task. The energy control between modules manifests a certain degree of thoughtfulness, in that the establishments of (successor, predecessor, and inhibition) links cannot abstain from thoughtfulness entirely. However, the thoughtfulness for energy control is limited to *reactions* of primitive behaviours, about which the relating circumstances are simple. To define such behaviours, simple automata would be suffice. No further deliberations over the world's conditions are needed, unlike the programming in traditional AI, the success of which relies heavily on programmers' deliberations. The success of Maes' arbitration between goals is grounded by, to a certain extent, pragmatist flow control.

The steps toward the accomplishment of a task can be regarded as being determined, via situated activities, in the pragmatist information flow. Pragmatism is a doctrine that emphasises determination by practical *consequences.* Correspondingly, the information flow, within the network of (global and sub-) goals, is regarded as being pragmatist in the sense that the global goals and subgoals are arranged according to their *practical* consequences in the real situations. Those practical consequences are foreseen by the activation-energy flow within the network of goals with the situations being taken into account.

The arbitration between goals, specifically, is mediated by the activation energy which is controlled by the non-zero-and-non-infinite γ/ϕ ratio and the robot's situated activities. Because both γ and ϕ have non-zero values respectively, the energy flow is controlled by the pursuit of goals under the circumstances of the robot's encountered situations. The plan for accomplishing the required task is neither grounded on functional analysis, nor purely opportunistic. It stands in between. That is, a certain plan emerges depending on the goals constrained by situations. The robot will arrange further goals and subgoals according to the encountered situations. Goals and subgoals are taken on the basis of their respective impacts in the encountered situations. The flow of activation-energy is subject to pragmatist control insofar as the robot takes account of its immediately encountered situations in its arrangement of goals. Although the encountered situations are *not tantamount to* the practical consequences of goals which are to be adopted, the derivation of those consequences depends on the situations. The derivation of (global and sub-) goals is really *determined* by the encountered situations, specifically under the design of action modules and the network connecting them. With such a network, the determination of goals, i.e. the arrangement of plans, is subject to pragmatist control.

Appendix B

Harnad's Explanation of the Symbol Grounding Problem

The symbol grounding problem concerns the connections between symbolic representations and the external world. Harnad (1991) presents a grounding scheme, of which the applicable assignment of semantic meaning to symbols are mainly subject to two tests – a formal test and a behavioural test.

The formal test is a test as to the representations which are formed in the shape of a formal/symbolic system. Harnad suggests that the symbolic representations are composed, at a lower level, of a *dedicated* symbol system, which has more constraints on symbol tokens than merely syntactic constraints. Unlike those of the higher-level system, the representations of such a lower level system are elementary representations: specifically they are nonarbitary shapes. Such lower level representations comprise the *iconic* representations and *categorical* representations, the former being analogues of proximal sensory projections of distal objects and events, and the latter being acquired or innate feature detectors that serve to pick out invariant features from the above sensory projections. Such representations are readily grounded, as Harnad argues, because they pass another test – the behavioural test, a test based on the discrimination and identification of objects and states of affairs, to which the elementary symbols refer. It is primarily this latter test that constitutes the behavioural capacity of the dedicated symbol system, which accordingly fixes the semantic meaning of the higher level system. As a consequence, Harnad states that he presents such a grounding scheme in the spirit of behaviourism.

Harnad views his grounding scheme as supportable by a hybrid connectionism[1], for the dedicated symbol system can be simulated in terms of connectionism, which supports the detection of invariant patterns out of the approximate sensory projections by 'exposure and feedback' (p. 344).

Behaviourism does not, in Harnad's grounding scheme, serve to explain all aspects of cognition; rather, it is proclaimed as being only applicable to the picking out of invariant features from the proximal sensory projections of distal objects and events. The terms 'exposure' and 'feedback' may be too simple to describe connectionism, but they manifest a general outlook of (behaviourist) association, which not only may serve to explain the grounding of elementary symbols, but also can be viewed as a basic type of connection *between* features of the external world *and* the internal mechanisms of organisms.

A Revelation. Of course, the above features of external world are not meant as the equivalent of ecological constraints. However, Harnad's grounding scheme may be taken to reveal that the signals an organism receives in the niche can connect to the organismic internal mechanisms under the support of behaviourist association, and that the behaviourist association may further connect to other types of information processing, such as connectionism.

Behaviourist association is deemed by Harnad not only to be the basis of symbol grounding – connection between an agent's *internal* mechanisms and the *external* world – but also as the type of processing at the lowest level, with the function of *pattern generation*, by extracting patterns out of proximate sensory projections. The present thesis will reserve the behaviourist association as a primordial connection between ecological constraints and organismic internal systems in the simplest cases of emergence (as is manifested most in simple types of training in low-level organisms), but propose an alternative[2] type of pattern

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[1] Harnad's idea is very close to the connectionism described in Smolensky (1988), which mainly consists of sub-symbolic representations and traditional connectionist processing. Smolensky claims that the PDP modelling here does not serve as implementation of those sub-symbolic representations, but derives them on the basis of connectionist associations.

[2] Self-organisation may be incorporated in connectionist algorithms. In this sense the PDP modelling and systems dynamics are not mutually exclusive mechanisms. Yet, they differ in the

generation, namely the self-organisation of dynamic systems, as is manifested in the internal dynamics of organisms. An interesting feature of external-internal association in the present thesis is, like traditional behaviourism, its dependence on multiple environmental determinants, on the one hand, *and* its result in providing certain initial conditions for the systems dynamics of internal systems (a significant deviation from traditional behaviourism), on the other. As a consequence, developmental factors would not suffice to *determine* the process of pattern generation in the organisms, but only serve to bridge ecological constraints and internal systems dynamics with the result of *initiating* the process of self-organisation in the organismic internal systems. Such a two-folded association will, unlike the attitudes of traditional behaviourists (Skinner 1971), not only enable us to reserve the autonomy of cognition within the internal systems, but also qualify us to explain the adaptability of organisms to the ecological factors in terms of the dynamics of organismic internal systems.

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sense that systems dynamics concerns characterisation at a higher level as to the interactions between control parameters, and concerns the effect of their interactions on the trajectories of interesting collective variables. In such a case, the PDP modelling and dynamic systems are directed to the same system in an ontological sense but are different in an epistemological sense, as they are characterised from distinct perspectives.

Appendix C

Sprite – Adaptive Local Navigation on account of Reinforcement Learning Algorithm

A task of navigation can be learnt in a two-dimensional environment with unmodelled slow-moving obstacles, as demonstrated by Prescott and Mayhew (1992), by their mobile robot 'Sprite' which has simple sensors, reflexes, and internal states. Because the obstacles are not only moving but also unmodelled, i.e. unknown previously to Sprite, and because Sprite can learn (within one hour) to navigate everywhere in different unmodelled environments, Sprite's capability for navigation can be seen as *adaptive*, as its designers (Prescott and Mayhew (1992)) claim.

The performance of perception *per se* does not seem to be active, because there is no indication as to what *selective* processes of navigation it can perform. Rather, Sprite is active with regard to its learning task. That is, the task of Sprite is the *active learning* (of navigation). Its learning process is active, as we will see, in the sense of selection over *learning processes*. This is a sense of active learning, as specified by Thrun (1995), in which agents learn not by staying stationary, but by interacting with the environment. Apparently Sprite learns while it is running in the field. Its learning of navigation is consequently active.

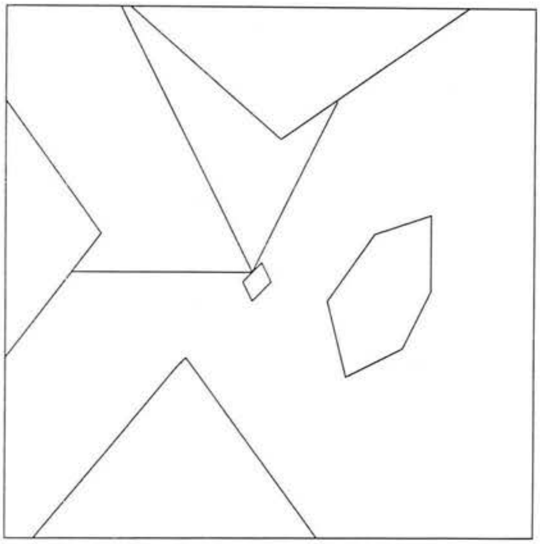

Figure C.1: **Sprite's Environment** Sprite emanates three rays in a two-dimensional world. Re-drawn of the Figure 13.2 of Prescott and Mayhew (1992), with modification.

Architecture.

Sprite's architecture is described as follows.

Sensors. Sprite has three ray sensors of *depth* heading in the left (−60°), right 60° and central directions 0°, together with an additional sensor of *touch*, which detects the collision of Sprite with a wall to an obstacle (figure C.1).

Reflexes. When it encounters an collision, Sprite has three reflexes that support it to reverse, rotate with a random angle between 90-180 degrees, and move off from its original heading direction.

Reactivity Accomplishment. Sprite's capability of reflex is purely *reactive*, in the sense that it responds only to the *immediate* sensor input, as opposed to any internal drive, such as a retrieved image. However, through organism-environment interaction within a short period of time, it eventually becomes capable of producing navigating trajectories.

Internal States and Reinforcement Learning. Sprite's capability of navigation is accomplished by an algorithm of reinforcement learning.

Reward. First, the sensor input is recorded, and the immediate reward r_t in the time t is assigned a value, specifically a negative value (as punishment) if colliding, and the value zero (as encouragement) if Sprite's current velocity rises up to 4/5 of its top speed. The value r_t is extended to computing the expected reward R_t[1] which is accumulated from time t to $t + k$, by

$$R_t = r_{t+1} + \gamma^1 r_{t+2} + \gamma^2 r_{t+3} + \gamma^3 r_{t+4} + \gamma^4 r_{t+5} + ...$$

where γ is the discount factor ($0 < \gamma < 1$). The multiplication of a γ value with an incremental degree can be understood as a value serving to capture the intuition that a later reward has a *less* powerful influence.

Policy Functions. A policy function controls the action to be carried out at a given state, i.e. $\Pi(x_t) = a_t$ where a_t is the action determined for Sprite to carry out at time t. In Sprite's architecture, a policy function has two components f and θ corresponding to the desired forward and angular velocities of the vehicle. They are converted by simple inverse kinematics into desired left and right wheel-speeds, where the third wheel acts simply as a castor in consideration of stability of the mobile robot. Thus, a policy function Π consists of an ordered four-tuple $(f_\mu, f_\sigma, \theta_\mu, \theta_\sigma)$, where ($f_\mu$ is the actions of left wheel when Sprite moves forward, etc.). The internal state of Sprite store five values in the course of learning – evaluation and this four-tuple.

The trajectory of Sprite's vehicle is controlled by a sequence of actions carried out in discrete time steps. In each time interval Sprite acquires new perceptual data from its sensors, then it generates *associated* responses, by performing one of the aforementioned actions, or by issuing a feedback signal that indicates a current collision, which will lead to a prevention of moving forward controlled by

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[1] R_t is named by Prescott and Mayhew (1992) as *expected discounted return*.

the evaluation system, followed by a reverse movement, a rotation, and a re-start (Prescott and Mayhew 1992, p. 209-210).

Evaluation and Error. A new state x_t (at time t) may be evaluated by a value $V(x_t)$, as Prescott and Mayhew (1992) consider, in an attempt to *estimate* the *accumulated* reward that Sprite will receive from time t onwards, if it keeps following the current (time x_t) policy $\Pi(x_t)$, which returns the action a_t to be taken at the current state x_t, e.g. moving straight forward or rotating with a random angle. The error $\varepsilon_{(t+1)}$ that happens at a later time (x_{t+1}) is defined as

$$\varepsilon_{t+1} = [r_{t+1} + \gamma V_t(x_t + 1)] - V_t(x_t).$$

In this definition, the error detected at time $t + 1$ is understood as the difference between the evaluation managed at the present state $V(x_t)$ and what can be estimated at a later time – r_{t+1} (i.e. the immediate reward) as a *realised* evaluation plus the discounted evaluation $\gamma V_t(x_t + 1)$ on the basis of the state (x_{t+1}) for the expected accumulated reward from the time $t + 1$ onward.

The estimated error ε_{t+1} can be used, as Prescott and Mayhew (1992) indicated, to predict the expected evaluation at the current state x_t (supposing that it is time t at the moment) according to an evaluation function introduced by Watkins (1989). Such an evaluation is of fundamental importance for a reinforcement learning algorithm, which needs to take account of the evaluation of a current state under expectation, given a current policy function Π (under the condition that it is held constant at all later steps). The evaluation system will be reliable if such an evaluation will always be *convergent* on a certain value for a given current state x_t, given that it has a certain policy function Π stored in the internal state. Prescott and Mayhew (1992) adopt a training method – the *gradient descent rule* introduced by Watkins (1989) – which he proves to be capable of converging in a sufficient trials:

$$V_{t+1}(x_t) = V_t(x_t) + \alpha\varepsilon_{t+1}$$

where α is a learning rate. With this training method, the expectation of the current policy function can be evaluated, which subserves the reinforcement learning algorithm undertaken to generate trajectories of smooth navigation in real-time.

Improvement of the Policy

The thrust of the reinforcement learning process is that the policies (actions) to be carried out are expected to improve in the course of learning, provided that the result of evaluating the robot states under control is rising. To improve Sprite's policy, Prescott and Mayhew (1992) use a method adopted by Williams (1988), where actions are represented in terms of random variables specified by *Gaussian probability distributions* and the policy is improved in association with the error $\varepsilon_(t+1)$. Note that the immediate reward and the evaluation of robot states are incorporated in the definition of the error ε_{t+1}. (see discussion in Prescott and Mayhew 1992, p. 207; for more details see Williams 1988).

Result

As an examination over the effectiveness of the adopted reinforcement learning algorithm, Sprite is tested for ten runs in a variety of environments, each of which runs fifty-thousand training steps (note its sample rate being 5 Hz, so the learning process with fifty thousand steps will not take a long time). In each test, Sprite does learn, as evident from two observations: the average distance of travel between collisions increase significantly from 0.9m (before training) to 47.4m (after training); and the average velocity is approximately doubled (note that moving fast is rewarded by an internal detecting function, as previously mentioned).

An impressive performance of Sprite is the demonstration of actions at wid*er* ranges. The learning system, in the beginning, undergoes an automatic *annealing* process (Williams 1988) which converges to a certain *local* maximum. Later, the width of each Gaussian distribution can increase provided that the local optimal mean value allows for more *exploratory* behaviour, as Prescott and Mayhew (1992) conceives.

The term 'explanatory behaviour' is sometimes used in the literature of active perception, e.g. Bajcsy (1988), but without further exposition as why *motor* activities, as opposed to language performance, can be regarded as explanatory. We can try to make sense of that term by seeing the motor activities that contribute to selection (over actions or learning processes) as being explanatory.

In the circumstance where the local optimal mean value allows for more exploratory behaviour, the annealing process becomes more global, as demonstrated in the implementation of Prescott and Mayhew's. Then, the range of acceptable actions becomes wider. As an example given by Prescott and Mayhew (1992), Sprite has a narrow range of acceptable actions when it is restricted to a tight corner. By contrast, the range of action performance becomes wider when it successfully moves to open spaces (p. 211). Prescott and Mayhew (1992) see this performance as showing an evidence that Sprite, after the reinforcement learning, is no longer limited to the performance of *reflexive* actions, although its architecture is purely reactive as aforementioned (p. 204). When its range of actions becomes wider, Sprite's policy function is improved, and thereby it is more competent to achieve a long-term goal, as is evident in a more complicated environment (pp. 204, 207).

In the above discussions, the learning process of Sprite demonstrates a type of embodied perception, on account of reinforcement learning algorithm, where perceptual activities[2] give rise to reward and evaluation of robot states, and thereby *previous* perceptual activities together with their motor actions contribute to train the robot in support of the gradually learnt navigating trajectories. The response in real-time is grounded mainly on two training methods, the gradient descent rule introduced by Watkins (1989), i.e. the convergence of evaluation in sufficient trials, on the one hand, and the training of policies (actions) established by Williams (1988), on the other.

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[2] Prescott and Mayhew (1992) claim that they have demonstrated a learning process in which previous *experiences* influence the generation of navigating trajectories.

The robot is a reactive device, yet it shows active learning with the effect of learnt competence from local to global navigation. The learning is active, in a sense different from the sense of being active for gaze control. Here, by contrast, the task is active learning. It is active because it learns in the course of interactions in the environment, specifically iterative trials of running and modifications of annealing processes – the processes of learning. More specifically, the interactions with the environment lead to the selection over the processes of learning, i.e. the annealing processes span from the local to the gradually more global.

If we see the gradually global annealing processes as a particular type construction, compared to the construction considered in developmental psychology, we can derive for later use a hint of activeness – construction of interacting activities with the environment (construction in the sense of gradual selection on the basis of previous selective outcomes) is an active process.

Appendix D

Active Perception in Relation to Non-Visual Modalities

It is natural to try and extend discussion of active *vision* to non-visual modalities, in order to evaluate the plausibility of proposing active *perception* as a general scientific paradigm (Bajcsy 1988). This has notably been done in the case of touch, and a number of studies have been done as active haptic perception (also called active touch) (e.g. Allen and Roberts 1989; Bajcsy 1985; Roberts 1989).

In this section we do not plan to review the active haptic perception research in detail; rather, we aim to highlight the possibility of extending active perception research from visual to haptic modalities. For this purpose the discussion will be divided into the following three parts. First, we present an example of active haptic perception, which is implemented by Roberts (1989); second, we discuss an example of active perception across modalities – the categorisation implemented by Scheier and Lambrinos (1996); last, we discuss the contribution of joint modalities research to active perception.

Adaptability at Three Levels. In this section we will see, via discussion of three types of robotic implementations, three levels of adaptability – adaptability by (1) changing the degrees of internal correlations between different components (which can be conceived as a change of *data*), (2) changing internal *processes*, and (3) changing *algorithms* of processing. These three levels of adaptability are demonstrated in the respective implementations by Scheier and Lambrinos (1996)

(Section D.3, Figure D.3), Roberts (1989) (Section D.1, Figure D.1), and Allen and Bajcsy (1985) (Section D.2, Figure D.2).

D.1 Active Touch on the basis of Optimal Surface-Tracing Moves

Roberts (1989) implements a robot system of haptic recognition, of which the task is to find a paired correspondence between 3-*D* polyhedral objects on the basis of two transformations – translation and rotation. That is, two objects are recognised as being correspondent to each other if they are mutually transformable (without changing their shape). As we will see, his implementation is a system of active haptic perception, like the aforementioned systems of active vision.

The problem of establishing the aforementioned correspondence is the identification of the equivalence of two polyhedral objects under translation and rotation. To respond to this question, Roberts develops a certain type of data structure to represent polyhedral objects, which is neutral to those two transformations; on the basis of that data structure, he develops a system which is able to identify the encountered polyhedral objects by certain activities of haptic exploration. After all, the haptic recognition on grounds of random search seems to be inefficient.

Architecture. In Roberts (1989), the method of recognising polyhedral objects consists of three steps. First, certain *geometrical constraints* are set between primitive components of the polyhedral objects – vertexes, edges, and faces. In the envisaged haptic recognition system, several geometrical relations are implemented for later tests. For example, an edge can be paired with another edge such that they are commonly adjacent to a face; a face can be paired with another one, where they are adjacent to each other. Based on such geometrical relations a polyhedral object can be represented in the form of tree structure,

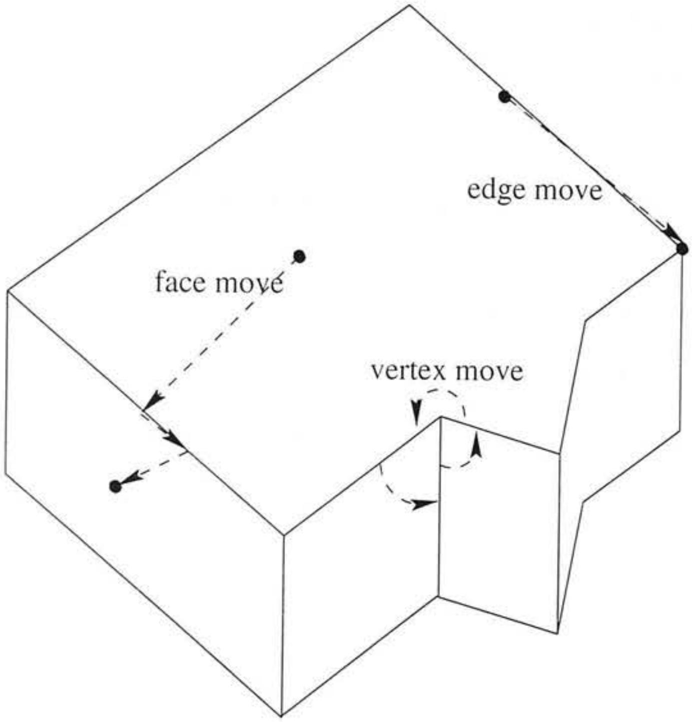

Figure D.1: **Roberts' System of Active Haptic Perception, with Three Admissible Surface-tracing Moves – Face Move, Edge Move, and Vertex Move.** Surface move is a trace across the face in a chosen direction until it reaches an edge; edge move begins at a point on it moving in a certain direction, out of the only two possible directions, until it reaches a vertex; vertex move is a move around (and hence near to) a vertex, which begins at a nearby position of the vertex, moving on a circular path until a new edge is reached.

which consists of the primitive components and adjacent relations. In Roberts' strategy of implementation, the matching of such tree structures constitutes a ground on which polyhedral objects can be identified.

Second, admissible *surface-tracing moves* are found, and for each move its cost is calculated, which is defined as the travelled distance (along the path of a move) weighted by a difficulty factor (given that different moves may have different degrees of difficulty). There are typically three types of admissible surface-tracing moves – those along a face, an edge, and around a vertex. The move along a face is a trace across the face in a chosen direction until it reaches an edge; the move along an edge begins at a point on it moving in a certain direction, out of the only two possible directions, until it reaches a vertex; by contrast, the move around (and hence near to) a vertex begins at a nearby position of the vertex, moving on a circular path until a new edge is reached. Such moves constitute the possible activities of haptic exploration.

With such explorations, the respective shapes of encountered polyhedral objects can *in principle* be identified, but Roberts has a further consideration as to the determination of a shape under the real-time constraint, which is important for any active perception implementation.

Third, among the admissible surface-tracing moves an *optimal* surface-tracing move is found as the *next* move. As defined by Roberts, an optimal surface-tracing move is the surface-tracing move that eliminates the largest number of *interpretations* with regard to the shape of the envisaged polyhedral objects. In addition, the *efficiency* of a candidate move is defined as the number of interpretations expected to be eliminated per unit of move cost; consequently, the optimal surface-tracing move is in fact the *optimally efficient* surface-tracing move.

Based on the geometrical representations of the polyhedral objects and the contribution of surface-tracing moves to possible interpretations, an optimal move can be obtained fairly simple by the following reasoning. For an encountered object, an optimal surface-tracing move can be determined, against a certain number of possible interpretations of polyhedral shape (to be represented in tree structures). Insofar as the data components have been collected, the respective efficiency of several moves can be examined. The efficiency of a single move can be determined by carrying out a surface-tracing move and counting the number of interpretations that are accordingly rejected. Thus, the efficiency of different moves can be compared, and a most optimal one can be found.

Roberts (1989) provides an example regarding the contribution of a surface-tracing move to the reduction of possible interpretations. As he puts it, a certain interpretation implies the condition that 'if we move along edge $E_{2,5}$, we will reach a vertex after travelling a distance of 2.3 plus or minus the data error bounds' (p. 11).

Such an interpretation can be tested with the aforementioned (vertex, edge, and face) moves, by testing whether carrying out the move along the edge with that distance leads actually to the reach of a (random) vertex. Because of its contribution to the test of possible interpretations, such a move, according to Roberts' strategy of active haptic perception implementation, is typically an *exploratory* activity that a robot can take in order to accomplish the required task, i.e. determining the shape of polyhedral objects via haptic exploration. With the above three steps, the identification of the encountered polyhedral objects can be maintained on grounds of their representations in tree structures, based on which two transformable polyhedral objects are seen as equivalent, and hence correspondent.

To summarise, the haptic perception implemented by Roberts (1989) is active, based on the gradually determined sequence of the optimal surface-tracing moves.

D.2 Tactile Information as a Complement to Binocular Depth in Support of Stereo Image

Tactile information can complement visual processing by way of active tactile exploration, as is demonstrated by Allen (1985) and explained in brief by Allen and Bajcsy (1985). The task of their works is to reconstruct[1] the stereo information of the objects with a *smooth* surface. They propose to support the visual processing (specifically the depth recovery on the basis of zero-crossings) by adding tactile information.

The problem of the visual processing relating to this task rests on the smoothness of the surface. Against the smooth surface, the recovery of a stereo image on the basis of zero-crossings is not supported by sufficient information. This is especially true under the circumstances of poor illumination. As is pointed out by Allen and Bajcsy (1985), 'neither edge features nor other variations are

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[1] Please refer to our later discussion of their concept of reconstruction, in connection with their *active* approach.

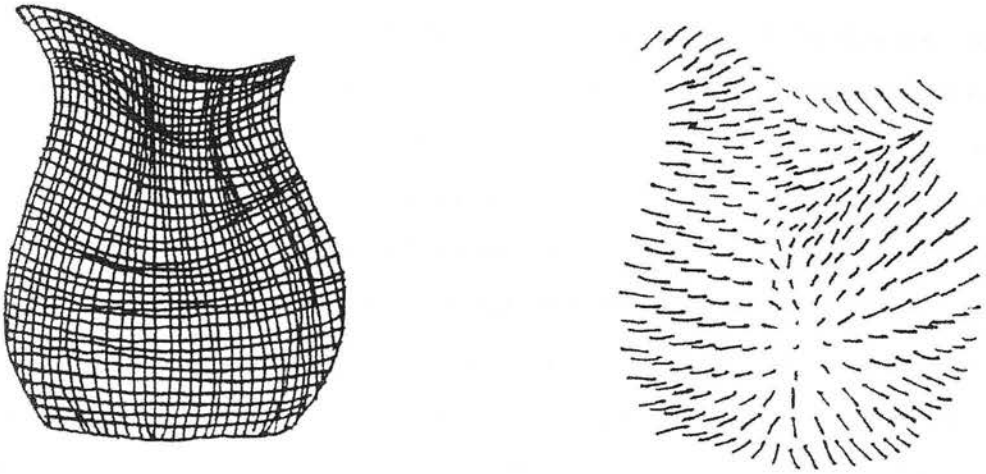

Figure D.2: **The Results of Active Tactile Sensing, Demonstrated by Allen and Bajcsy (1985).** Left: the integration of stereo contour information and active tactile sensing. Right: the surface normals computed from the surface in the right figure. Re-drawn with configuration from the figures 4-2 and 4-3 of Allen and Bajcsy (1985).

present in these [homogeneous] regions ...' (p. 3). It is not difficult to realise that the smooth surface looks virtually like a homogeneous region, for there is no sufficient visual information to mark such differences on such a surface.

Although visual processing does not suffice to reconstruct the stereo conditions of the surface, it may be sufficient with *additional* supports from *other modalities.* A resolution is provided by Allen and Bajcsy (1985), which they name as active tactile exploration, on the basis of the information made available by force/position sensing and pressure/position sensing. Their strategy, in brief, is to support visual processing with the tactile information extracted from the curves (detected by the force/position sensing and pressure/position sensing) of the tactile boundary, differentiate them, scale the tangents to reflect the change of parametric information, e.g. the distribution of surface normal (i.e. the direction perpendicular to the tangent line at a surface point) (Figure D.2). To make available such tactile information, the haptic system finds a surface contact and traces the tactile surface of the visually smooth regions, which in their implementation amounts to the whole surface of a pitcher.

The tactile information is integrated with the visual information (i.e. the zero-crossings), by first preserving the readily available visual 'parameterization', secondly additionally making available the tactile information, and then combining these two sources of information (p. 5). The added tactile information, specifically, is computed globally based on the changes of the aforementioned parameterization, which are reflected in the differentiation of the curves and the scaling of the tangents, as seen in figure D.2. Note that the computation of zero-crossings is based on the points matching at local regions. The addition of the global information must be combined with the local information consistently. The integrated visual and tactile (thus the local and the global) properties, are regarded by Allen and Bajcsy (1985) as higher level surface descriptions that can be used for surface matching, like lines and corners, as opposed to the low level properties such as local stereo matching.

It is worth noting that the integration across modalities takes effect only when the surface is smooth, otherwise the information on zero-crossings would be sufficient for the recovery of the stereo surface. Thus, the higher level integration and the condition of smoothness consists of a basis for considering why the implementation of Allen and Bajcsy (1985) conforms to the active perception approach.

Reconstruction. Recall that the required task in Allen and Bajcsy (1985) is to *reconstruct* the stereo information of the objects with a smooth surface, and that they support this task by seeking the visual information of zero-crossings and via the *active* tactile exploration. The appearance of these two terms in the same paper may be seen inconsistent, because the active perception perspective does not seem to view the perceptual processing as a process of reconstruction. Indeed, the stance against reconstruction is the beginning point of the active perception perspective. For this point, see our discussions in Section 3.2.

Yet, Allen and Bajcsy (1985) do actually use both the terms 'active' and 'reconstruction' in the same paper. In their abstract, it is written that '[w]e ... argue that other sensory information is necessary for more complete surface *reconstruction* (italics added).' In the text, it is stated: '[t]he approach being followed here is that relatively sparse visual data ... is supplemented with *active* tactile exploration (p. 2; italics added).'

Under a sympathetic reading, the inconsistency can be eliminated by considering that the reconstruction envisaged by Allen and Bajcsy (1985) does not begin *entirely* with the *retinotopic maps*, which is the specific circumstance of reconstruction challenged by the active perception perspective. Other processes need to be manipulated in support of the required tasks. As Allen and Bajcsy (1985) argue, the reconstruction of stereo information needs to be complemented by tactile information. They specifically deny the effectiveness of reconstruction which is entirely beginning with the retinotopic maps.

One may still cast doubt on the active status of the implementation, by arguing that the combination of visual and tactile information ends up with a common ground for reconstruction, for reconstruction may be pursued across modalities.

To respond to this challenge, consider how Allen and Bajcsy (1985) implement the visual and tactile integration. As we have discussed, the implemented integration across modalities is grounded first on the condition of smoothness and the higher level integration. Regarding the smoothness, the two modalities do not stand equally on the same common ground, because the tactile sensing is carried out only on the condition of surface smoothness. In other words, the tactile processing takes effect under conditions, and consequently occurs later. Regarding the higher level integration, the visual and tactile information is combined consistently with a level difference, in that one is local and the other is global. Specifically, the local parameterization is preserved, and the global information is the *changes* over the local parameterisation. As the information at a global level, the tactile information does not stand on its own, but instead presumes the visual parameterization, by specifically computing its changes, thus a higher level computation. The eventually combined properties, as a consequence, stand on a higher level. Hence, the visual and tactile information do not stand on a common ground for the reconstruction across modalities, and thus do not accord with the reconstructionist assumption that sensory information stands as the beginning stage of processing.

Summary. As a brief overview of the visual-tactile integration implemented by Allen and Bajcsy (1985): it is active because the tactile information is manipulated (by hand movement) to support visual processing when needed, with the effect of bringing about integrated information and thereby reaching the required task (the reconstruction of a stereo surface) more effectively.

D.3 Active Categorisation Across Modalities

The active competence of categorisation implemented by Scheier and Lambrinos (1996) is jointly subserved by visual and haptic modalities, unlike the implementations of active vision. It is straightforward to realise that the role of haptic sub-systems is important, because without them the identification of conductivity would be utterly impossible. Interestingly, the role of the visual sub-systems is equally important, for without them their robot could not eventually learnt to identify remote objects, find them uninteresting, and ignore them. The robot would then be unable to categorise objects simply on grounds of visual modality, which the implementation with joint modalities is capable of, in contrast.

The advantage of active perception with joint modalities lies in the identification across modalities. That is, the identification of properties of a modality can be carried out by systems of another modality. In our discussion, the categorisation of objects with the property of conductivity, a haptic modality, is eventually carried out by visual systems only, as is evident when the robot can *ignore* un-interesting objects without touching them at all.

In this implementation it is not the case that the visual systems *or* the haptic systems are active. Rather, it must be that the *whole* system of categorisation is active.

An Implementation of Categorisation According to the active perception perspective, categorisation can be representation-free, unlike the traditional perspective, the processing on account of hierarchical modules. Categorisation of a certain domain, e.g. food, is traditionally seen as a module of high-level perception, which takes effect by dealing with the output of *previous* modules, i.e. lower level ones in the hierarchical order. Because it deals with the outcomes of those previous modules, the processing of categorisation presumes representations. In contrast, the active perception perspective may see categorisation in a different way, as a result of sensory-motor coordination, suggested by Scheier and Lambrinos (1996). They design a mobile robot for recognising and discriminating objects of different types, on the basis of the sensory-motor coordination of two modalities, as they claim, namely visual and haptic modalities.

Overview of the Architecture. In overview, their mobile robot is implemented with visual and haptic systems, which are connected by re-entrant correlations. Each system consists of four parts, to wit a sensory *map*, a motor map, an attention map, and a feature map (Figure D.3), each of which comprises a number of nodes connecting to the nodes of other maps. Between the sensory map and the motor map lies a connection, called the *attentional sensory-motor loop*, which is a feedback loop linking categorical responses, i.e. the motor responses to sensory inputs, with the attention map. The attentional sensory-motor loop is gradually *modulated* in robot-environment interactions. The main strategy of implementing categorisation consists of the modularisation of the two attentional sensory-motor loops respectively, on the one hand, and the re-entrant connections between those two modulated attentional sensory-motor loops, on the other. Such a strategy can be discussed in detail as follows.

Modularisation. The attentional sensory-motor loops of both modalities are modulated, with respect to visual and haptic modalities, in that the sensors are gradually directed, as a result of sensory-motor coordination, toward certain salient sensory stimuli, such as light.

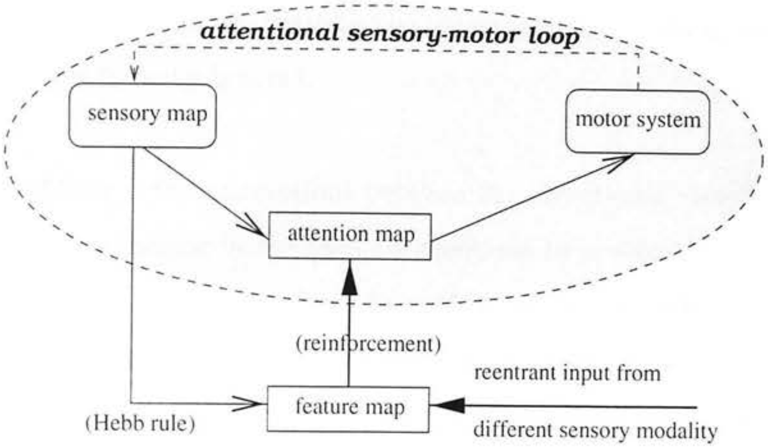

Figure D.3: **The Categorisation Robot implemented by Scheier and Lambrinos (1996).** Re-drawn with configuration from Scheier and Lambrinos (1996), figure 4, p. 69.

The attentional sensory-motor loop with respect to visual modality (in short, the attentional *visual*-motor loop) responds selectively to light. Later, wheels of the robot move by orienting the robot[2] toward the direction of the source of light. The bright part on the top left, as an example provided by Scheier and Lambrinos (1996), will lead to a certain allocation of the attention map which causes forward translational and left rotational movements. Furthermore, the visual-motor loop is modified gradually in the course of subsequent (visual-motor) coordination activities influenced by the re-entrant connections across modalities. The modularisation of visual motor loop results from the iteration of such modifications.

Like the attentional visual-motor loop, the attentional haptic-motor loop is modulated, specifically by conductive materials. For this specific robot, it explores properties of the targeted objects only by the haptic modality, while vision serves simply to guide the robot in question near to those targeted objects. The attentional haptic-motor loop, is controlled by Hebb's rule, which similarly leads to lateral inhibition. The modulated attentional haptic-motor loop drives the robot to carry out appropriate motor activities in support of object exploration,

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[2] For the robot in Scheier and Lambrinos (1996), the front side, to which the robot is to orient, must be the side where *both* the visual sensors and the arms are located, in order to facilitate the visual-haptic re-entrant connections.

specifically lowering the arms, grasping the object, and only picking up *conductive* objects with others being ignored.

Feature Maps. The connections between the attentional visual-motor loop and the attentional haptic-motor loop are mediated by a visual feature map and a haptic feature map. As seen from figure D.3, a feature map, say the visual feature map, receives inputs from both the (visual) sensory map and the haptic feature map; in addition, the feature map feeds forward to the (visual) attention map.

Regarding the inputs from the (visual) sensory map, the feature map responds selectively to textures, specifically the horizontal and vertical edges, with the corresponding nodes in the feature map being activated; on the other side of a coin, for the non-responding inputs, their corresponding nodes in the feature map are inhibited, so that those inputs are virtually 'ignored' (p. 71). Later, the neighbouring nodes in the feature map are regulated by Hebb's rule, in order to enhance the activities of the feature map *locally* by lateral inhibition. As a result, the horizontal and vertical edges of the given target object are selected, as the visual characteristics of the categorisation at issue.

The (haptic) feature map is trained in a similar way, so that certain haptic features are selected (in Scheier and Lambrinos (1996), it is solely conductivity), as the haptic characteristics of the envisaged categorisation.

Re-entrant Connections. The selected characteristics of different modalities must be connected to completed the categorisation in question. This is done by the re-entrant connections between the feature maps of two modalities. Their correlations are affirmed by reinforcement learning, which is mediated by a value system, consisting of a limited number of nodes. The reinforced weight is fed backward to the visual attention map and the haptic attention map, respectively. Eventually, the attentional visual-motor loop and attentional haptic-motor loop are mutually coordinated, in support of the recognition and discrimination of conductive objects located randomly in the environment, as is evident in the experimental result achieved by Scheier and Lambrinos (1996). Thus, the robot is trained to perform the task of categorisation successfully, with regard to conductivity.

Active Categorisation This implementation of categorisation is grounded on the gradual modularisation of attentional sensory-motor loops (of the visual and haptic modalities, respectively), on the one hand, and the re-entrant connections between feature maps of the two modalities, on the other. Throughout their design, Scheier and Lambrinos (1996) do not adopt hierarchical modules in their architecture. Hence their approach to the robot architecture is not reconstructionist.

Simply because their approach is not reconstructionist, Scheier and Lambrinos (1996) see their implementation as an instance of active perception. They claim that their implementation of categorisation in the mobile robot is grounded on sensory-motor coordination, but not on hierarchical processing.

It is reasonable to argument that the categorisation implemented by Scheier and Lambrinos (1996) is active, because the robot's association with the targeted haptic feature (i.e. conductivity) leads to the selection of its visual features and consequently gradually circumscribes its subsequent targets of exploration, given that more and more objects are gradually ascertained to be non-interesting.

In more detail, the active categorisation, specifically the active recognition and discrimination of the objects of certain visual and haptic properties (i.e. conductivity, and its associated visual properties, in this particular robot implementation), is accomplished, on grounds of reinforcement learning, which is autonomous. The *reinforcement learning* maintained in the re-entrant connections between the visual feature map and haptic feature map first associates conductivity with certain visual features, and accordingly gradually modulates the attentional visual-motor loops, also on grounds of reinforcement learning. In the course of reinforcement learning, the robot gradually *focuses* on certain visual characters which are associated with the targeted haptic feature (conductivity).

The robot, thus, can be understood as being interested in just those objects. In addition, the 'interest' is not only realised in the weights of the attention maps but also in bodily movements (moving toward)[3], by the attentional visual-motor loop and attentional haptic-motor loop. The robot turns out, insofar as the present implementation of categorisation can control, *only* to move toward conductive objects and to *only* grasp those types of object.

The implemented categorisation can be seen as achieved through *active* learning. The learning is seen as active in the sense that the gradually achieved category (i.e. Conductivity), through gradually narrowed focuses in the selection of visual materials, can be seen as resulting from the *construction* of interacting activities with the environment, like the construction understood in the case of Sprite (see Section C, page 367). Like the construction understood in the case of Sprite, here the construction is understood in the sense of gradual selection (over the categorised materials) on the basis of previous selective outcomes – specifically the gradual modularisation of the attentional visual-motor loops. Remember that the active learning of Sprite is also implemented with the reinforcement learning algorithm. This is an evidence indicating that the reinforcement learning algorithm can serve to implement active learning.

D.4 Summary of Non-visual Active Perception

The present theories and implementations of active perception research are mostly focused on visual modality. A goal of the present thesis is to bring active perception beyond the limitation of vision modality. This attempt is supported in two steps. Firstly, attention of the present thesis directs to active *haptic* perception, by discussing the robot implemented by Roberts (1989), which accomplishes the task of identifying polyhedral shapes by stepwise determination of an optimal surface-tracing move for a next step of haptic exploration. As it turns out, the steps of robot exploration gradually narrow down the possible interpretations and

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[3] By contrast, the oculomotor activities of the visual attentional visual-motor loop remain functioning. Bear in mind, besides, that there would be no movements of arm and grippers for those objects that are not even approached to by the attentional visual-motor activities.

eventually single out the geometrical shapes of the given polyhedral object. The previous definition of active perception is indeed extended from visual modality to haptic modality. This implementation exemplifies the active perception with a non-visual modality.

The second step is to show *cross-modal* active perception, which is exemplified by two implementations – Allen and Bajcsy's robot of visual-tactile integration and Scheier and Lambrinos' robot of active categorisation. The former robot carries out the task of shape identification, even to identify a transparent curvature. The robot demonstrates that information of a non-visual modality is sought when it is needed to *complement* visual processing in support of the required task. According to the definition of active perception, the robot of Allen and Bajcsy's shows across-modalities active perception.

The latter (Scheier and Lambrinos') robot maintains visual categorisation of a haptic property – conductance. The robot the association gradually *circumscribes the subsequent targets* of haptic exploration with certain visual features, and thereby successes to associate conductible objects with their visual features. Because it can stepwise circumscribes its subsequent targets for accomplishing its task (categorisation), this robot is a active perception system.

Appendix E

Indexes

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E.2 Index of Definitions and Expositions

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References

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