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Yasushi Ando

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Contact Address:
Department of Computer Science
University of Bath
Bath, BA2 7AY
United Kingdom
URL: http://www.cs.bath.ac.uk

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THE EFFECT OF PREDATION ON THE EVOLUTION OF DOMINANCE HIERARCHY IN PRIMATE SOCIETY

submitted by

Yasushi ANDO

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Declaration

This dissertation is submitted to the University of Bath in accordance with the requirements of the degree of Master of Science in the Department of Computer Science. No portion of the work in this thesis has been submitted in support of an application for any other degree or qualification of this or any other university or institution of learning. Except where specifically acknowledged, it is the work of the author.

Signature of Author ....

Yasushi ANDO

Abstract

In the dissertation, a framework to support constructing a MAS simulation is built. The framework makes a point of simplicity both for constructing a model and for conducting an experiment. Taking advantage of it, the effect of predation on the primate society is investigated. The result shows the probability for predation to affect dominance aspect of primate society.

Acknowledgements

I would like to thank Dr. Joanna Bryson for sparing her precious time to meet individually and in group. All comments given by her helped for me to improve the dissertation. I thank Maki to send all Japanese books as well as Japanese food. Without them I must not complete the studying abroad. Lastly, I really appreciate all people I have met in UK.

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Part I

Introduction

Chapter 1

Introduction

No one can deny the idea that the human society is unique to animal societies. It is, however, not reasonable to deem the human society to be completely different from the others. Rather, a human is a kind of animals; accordingly, the origin of human society and those of other animals' must be continuous somewhere (Sugiyama, 2000, p. 110). Especially primate society is so sophisticated that it can be compared with humans. For example de Waal observed political behaviours such as struggling for power, allying, and mediating in Chimpanzee (*pan troglodytes*) society (de Waal & de Waal, 1998). In other words, to research the structure and origin of primate society can be connected to research human society itself (Sugiyama, 2000, p. 133).

There are a lot of factors to affect a structure of primate troops (maybe including human society): habitat, food, climate, the size of body, and so on. Predation is one of these factors. Most families belonging in primates do not have many danger to be eaten because of their features (see Section 2.1.4) so that some researchers suppose predation does not affect primate society very much (Miller, 2002, ch. 10). However, it is fact that its impact is not evaluated correctly so far. The hurdles to evaluate it result from the difficulty of observation. In addition to the little number of predation, the existence of observers may restrain predators from preying. Computer simulation may be able to supplement these weaknesses because it allows concentrating specific aspect of an event (see Section 1.1).

Most group-living animals, including primate, regard dominance as the most important because it brings various advantages to predominant individuals such as easy access to candidates for mating and food (Hemelrijk, 1999*b*). One of the benefits is safer place. That is to say, being at the periphery of a group is more dangerous than being at the centre because predators may attack a victim on the fringes of troop; consequently, predominant individuals tend to occupy the central, namely safer, position. Hemelrijk demonstrates that such arrangement emerges from individual dominance interactions with simulation. She, however, has not built predation into her model, because she dismissed its influence by reason of the fact that "spatial centrality is also observed among organisms that are not menaced by predators" (Hemelrijk, 2000*a*, p.6). The aim of the dissertation from the viewpoint of primatology is to verify the influence of predation on the evolutional dominance hierarchy on the basis of Hemelrijk's model.

Hemelrijk modelled primate society by what is called Agent-based modelling (abbreviated 'ABM' afterward). In ABM, target fields are modelled not in theoretical way but by interaction of agents (Axelrod & Tesfatsion, 2005). Each agent mainly decides its action in nearsighted way so that the emerged phenomenon cannot be anticipated completely. Although it may sound strange, the indecisiveness is suitable to simulate animal society (including humans) because society itself is also uncertain (see Section 2.2.3).

The basic structure of ABM is almost common; it usually consists of the environment where agents interact with each other and agents which can decide its action independently. Accordingly, various multi-agent simulators which can help both constructing and evaluating ABM are provided.

Roughly speaking, there are two significances in the dissertation from the viewpoints of both researching primate society and the tool for it. They are respectively expressed below.

1.1 Objective In Primatology

The arrangement that more predominant individuals position themselves in more centre and less dominant on fringe is often observed in monkey troops (Seyfarth & Cheney, 2002). Hemelrijk demonstrated that the arrangement is emerged from their dominant interaction (Hemelrijk, 2000*a*). The hypothesis, however, does not intend to explain which environmental pressure promotes the dominant nature of monkeys. Although it is generally said that the pressure may be food, predation, or both (Miller, 2002), there is no decisive evidence. The primate society is so complex that it is really difficult to extract one causal relationship from actual observed behaviours. A simulation is useful to analyse such complex phenomena (see Section 2.2.3) because it allows for researchers to ignore redundant factors and to concentrate on important ones.

The scene that a primate is caught by a predator has hardly been observed (Jolly, 1972, p. 70). For example, Miller wrote that she could not have observed any predation for about four year when she engaged in research at Hato Pinero (2002, p. 97). The fact, however, does not contradict the importance of predation in the society of primates. Granted that almost no one have directly seen the predation, the evidences that infant primates are eaten are often detected. In addition, the influence of a predator is sometime supreme. There is a record that vervet monkey mortality is originally about 50% at Amboseli, Kenya; however, once one leopard appeared on the site, it increased to 70% (Thierry et al., 2004, p. 90). A simulation can supplement the lack of observation. That is to say, by a simulation, researchers can confirm whether or not a hypothesis can connect observed initial state and observed result without directly observing the process.

This dissertation simulates primate behaviour with concentrating on dominance aspect of primate society and predation. If less-dominance tends to suffer predation, it is likely that predation is one of environmental pressures causing dominant nature of primates.

1.2 Objective In Developing MAS Framework

Each existent MAS (Multi-Agent System) toolkit has its own advantages and disadvantages; however most of them seem too rigid to improve a model on them by trial and error. Because it cannot be decided what kind of model can represent a monkey society before some trial, agility is a key feature of the simulator for the dissertation.

Although NetLogo (Wilensky, 1999) is kind of a good selection for the purpose, the attached development environment seems too simple for an experienced programmer. It does not mean that the experimenter is limited to a novice in programming. Of course beginners must be able to use the simulator; and moreover it is desirable that the more familiar with it an experimenter becomes the more effectively the experimenter utilises it.

Accordingly, in advance of the investigation of primate societies the simulator for it is developed. In the simulator agility is made the most of in order to deal with a variety of models and to modify them easily. In addition it should accommodate beginners and experts.

Chapter 2

Background

Brief introductions about whole background knowledge for a reader are available here. If you are familiar with the fields oriented the dissertation, namely agent-based modelling and primatology, you can jump this chapter.

Because the purpose of the dissertation is to simulate primates' behaviour, knowledge of both simulation and primates are required. Furthermore, the account of simulation can be divided into simulation itself and a tool for it. Primates, simulation, and simulator are explained in sections named Subject, Method, and Tool respectively. Stating about the method adopted by the dissertation in more detail, it is called Agent-Based Modelling (hereafter ABM), which is regarded as the core thesis in the Method section. On the whole, what ABM is, how to apply it to primates' behaviour, and how to implement it are explained there.

The fields mentioned in the dissertation are fairly broad. To make the relationship of backgrounds both with each other and with latter parts of the document clear, please see Figure 2-1.

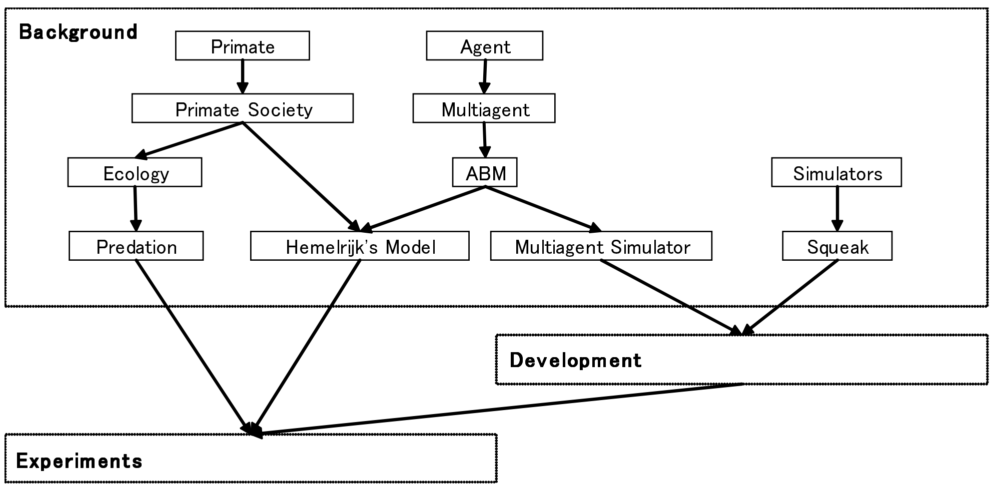


Figure 2-1: Relationship Between Each Topic

2.1 Subject: Primates and Predators

2.1.1 Primate

First of all, primate itself must be explained. Families included in primates are relatively broad comparing to other mammals; they are from lemurs to humans (Ankel-Simons, 2000, p. 1). Owing to the diversity, it is difficult to define primates. There may be not any feature not only held by all primates but also unique for primates. One example of an anatomical definition is the following:

> Primates can be defined as placental mammals having orbits encircled with bone, with clavicles present, and with flat nails on at least some digits. The brain tends to be large relative to body size and shows a posterior lobe and triradiate calcarine sulcus (*note is omitted.*) as well as sylvian fissures (*note is omitted.*). (Ankel-Simons, 2000, p. 37)

It is a good approximation that primates are arboreal mammals excluding squirrel and sloth (Nishida & Uehara, 1999, p. 31). In fact, most of primates' feature can be accounted on the basis of the definition. Thumb located on the opposite side of other four fingers is recognized as one of primates' characteristics (Napier & Russell, 1985, p. 53), and it must come from to grab a branch. It may be the same reason for the flat nails as pointed above. Two orbits in front of nearly spherical skull (Napier & Russell, 1985, p. 53) are required to visually grasp the correct distance to the branch to catch; additionally, because of the difficulty to handle three dimensional vision, someone even says it is the reason for primates' relatively large brain (Ankel-Simons, 2000, p. 139). Moreover, because parents have to hold their infant while their troop wander from branch to branch, primates usually have single offspring at a time(Ankel-Simons, 2000, p. 37). This of course affects private society sinice each offspring is a significant investment.

It may be natural to wonder why human is so different from other primates, although de Waal has shown the primate society is more similar to human's than it is thought so far through her research on Bonbo (*Pan Paniscus*) (1998). Some researchers attribute the reason to human's leaving woodland, then they research monkeys living on the periphery of a forest because they may be similar to early human [1] (Sugiyama, 2000, p. 110).

2.1.2 Primate Society

Sociability is one of important characteristics for the primates (Napier & Russell, 1985, p. 61). Like other features, the structures of primate society are significantly diverse. The diversity can be seen in not only whether or not they are in a group but also how they troop. While orangutan (*Pongo pygmaeus*), nocturnal *Strepsirhini*[2] and so on live solitarily, most of modern

[1] A few researches speculate that the key to solve the mystery of human evolution is in the waterside. In other words, human had once become aquatic after leaving woodland. See http://www.primitivism.com/aquatic-ape.htm

[2] Lemurs and Lorises are included

TYPE	EXAMPLES
Solitary	Aye-aye[3], Sportive lemur[4]
A male & a female	Marmosets[5], Siamang[6]
A male & females	Guenon[7], Howler[8]
Males & a female	Mustached tamarin[9]
Males & females	Red Colobus[10], Macaque[11]

Table 2.1: The structures of primate troops

primates make a group (Nishida & Uehara, 1999, p. 281). The structures of primate troops can be roughly classified by the proportion of adult male to adult female (cf. Jolly, 1972, p. 101, Table 10).

Note that these styles of troop may not be static. In many species, migrant individuals, which do not belong to any troop, exist and they sometimes interchange a member of a troop (Napier & Russell, 1985, p. 65). In addition, it is likely that the same species troop in different way according to habitats (Sugiyama, 2000, ch. 17).

The troop taken as an object of the dissertation consists of multiple males and females. Accordingly general characters of such multi-male/multi-female troops are stated below although there is no characteristics shared by all primate troops as stated so far. It is widely said that the most important resource depends on sex. Males make a point of accessibility to prospective mates while females do food because of their gulf of load for reproduction (Miller, 2002, p. 154). The difference might remarkably affect the structure of primate society; that is, females evenly disperse in a site for foraging while males aim for place in which the density of females is high. Because the area where females disperse may be narrower than the area for food, contests between males for good position can become severer than that of females. The balance of these resources might lead a variety of dominance style (Thierry et al., 2004, ch. 8).

A member whose status is so below that it cannot access to resources can do nothing other than leave the troop. By reason of it or not, one gender stays the troop in which it was born whilst another gender leaves and looks for other troops when it grows up in most multi-male/multi-female troops (Thierry et al., 2004, ch. 9). In other words, the troops are matrilineal or patrilineal (Nishida & Uehara, 1999, ch. 12). The fact means that primate society is affected by kindred. Although relationship between mother and her children tends to be stronger than that of father and his son in multi-male/multi-female troop because a father has no way to know who is his child. Concerning males relationship, it is also observed that brothers cooperate each other. (Nishida & Uehara, 1999, ch. 11)

[3] *Daubentonia madagascariensis*
[4] *Lepilemur mustelinus*
[5] *Callithrix*
[6] *Hylobates syndactylus*
[7] *Cercopithecus*
[8] *Alouatta*
[9] *Saguinus mystax*
[10] *Colobus badius*
[11] *Macaca*

2.1.3 Ecology

Topics about a primate and primates are introduced so far. Then relationship between primates and their surroundings is mentioned in this section.[12]

One of typical interactions of animal with environment may be food. Primates are generally able to eat diverse foods: fruits, leaves, insects, and meats (Jolly, 1972, ch. 3) although it was thought that primate basically did not eat meat and human was only 'meat-eating primate' at one time (Nishida & Uehara, 1999, preface). Some kinds of primates even eat their infants under particular condition (Sugiyama, 2000, ch. 16). The diversity of primate society may come from this tolerance of food because eating can profoundly influence a troop structure (Figure. 2-2). If they mainly eat food which can be easily found but not so nutritious, the species must

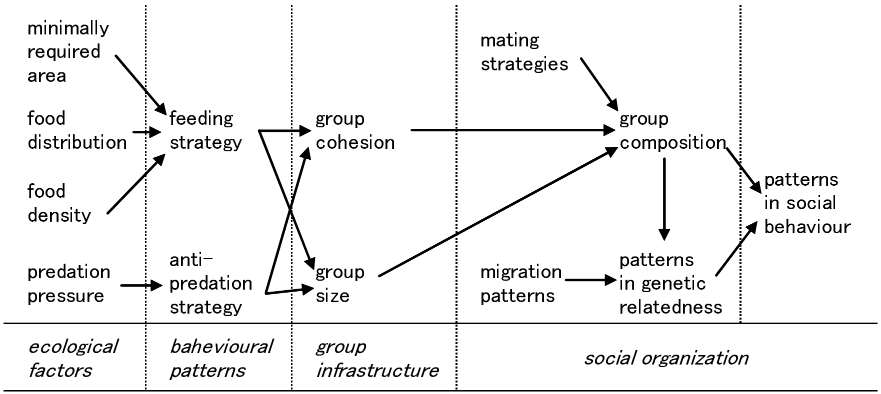


Figure 2-2: Scheme showing the way in which primate social organization is determined by external (ecological) factors. (van Schaik & van Hooff, 1983, Figure 1.)

spend much more time for eating than foraging. Such troops may not require strict hierarchy because the effort to aggress an opponent is greater than the profit brought from the result. It is more reasonable to seek food by itself than to rob others of food. On the contrary if they prefer nourishing but hardly found food, they must spend longer time to foraging. Food must be in centre of their timetable.

Needless to say, food affects territory and home range too. The fact that primates can eat diverse food means that they can live in various places. The primates range about from latitude 40 degree N to 40 degree S (Napier & Russell, 1985, p. 9). Some primates fill their mouth with colourful fruits at the Equator while others play a snowball fight in snow field (Brakefield, 2005). In addition, their adaptability is remarkable. Not only one primate can forage forest, meadow, coast, and any other place but they can change their habitat in short time. Some of Japanese macaque troops change their habitat from deep forest to periphery of city in only 20 years and it has become social problem (Sugiyama, 2000, ch. 10).

Although it is written as if food is centre of all other characteristics to simplify the explanation, it must be noted that they have varied effects on each other. Nocturnal monkeys are

[12]Humans are ignored in this section because we live almost everywhere and are ultimately omnivorous.

difficult to find and eat diurnal insects. Food for primates living in special habitats such as precipice must be considerably limited. These interactions of features form diversity of primate society.

2.1.4 Predation

Not only eating but also being eaten has an effect on primate society. Opinion is, however, divided on how critical predation is. Actually the risk of being eaten for most of primates is not very high because of their large body size (Thierry et al., 2004, pp. 90-91). In fact, however, not predation itself but primates' fear of being eaten has more important influence on structure of troops. In other words, if they feel risk of predator they must be in reactable formation to predators even in the site where there is not any of them (Miller, 2002, p. 138). Beyond question vigilant behaviours against predators[13] can be seen regardless of actual existence of them because the behaviour is executed to know whether predators exist near the monkey or not.

Predators Predators which prey on primates are divided into three types: mammalian carnivores, raptors, and snakes. Each type is briefly described below.

Mammalian carnivores For example, leopards (*Panthera pardus*), lions (*Panthera leo*), fossas (*Cryptoprocta fossa*), and jaguars (*Panthera onca*). Carnivores are more various than other types. They can be divided into two groups: scansorial (means species which can climb a tree) or not. In addition, their styles of hunting are varied; one individually attacks, another tends to ambush, and others cooperate to prey (Miller, 2002, ch. 7).

Raptors For example, barn owls (*Bubo bubo*), savanna hawks (*Heterospizias meridionalis*), and crested eagles (*Morphus guianensis*). Although few of them are large enough to capture an adult primate and they mainly attack an immature or infant, it is occasionally observed for them to capture an adult (Miller, 2002, p. 121).

Snakes For example, Boa constrictors (*Boa constrictor*), and reticulated pythons (*Python reticularis*). They can be seen in a tree, but may be less agile than primates to move in a tree (Miller, 2002, p. 74).

Interesting to say, predators which affect an primate society the most may be primates itself. Chimpanzees(*Pan troglodytes*) often eat other primates; especially red colobuses (*Colobus badius*) tend to fall a victim to them (Sugiyama, 2000, ch. 3).

Anti-predator behaviours Behaviours when primates find a predator are classified into six categories and they may depend on distance toward and type of a predator.

Alarm calling The first member of a troop which detects a predator usually gives the alarm although the reason why it do regardless of increasing its own danger is unclear (Miller,

[13] "an animal was considered vigilant when its head was up and its eyes open." (Miller, 2002, p. 191)

2002, p. 39). Interestingly the alarm call is not always uniform. Most primates choose the alarm according to the fact that the predator is terrestrial or aerial. Vervet monkeys (*Chlorocebus aethiops pygerythrus*) use one more alarm for snakes. (Nishida & Uehara, 1999, ch. 7)

Fleeing If the alarm call is for carnivore, members climb a tree nearby, while if for raptorial they just look up the sky. In the case of vervet monkeys (*Chlorocebus aethiops pygerythrus*) heard alarm calling for snakes, they stand up and become more vigilant probably because they can avoid being caught as long as they evade snake's surprise attack (Nishida & Uehara, 1999, ch. 7).

Mobbing Primates sometimes get together when they notice the existence of predators (Miller, 2002, ch. 6). The behaviour is called mobbing. Although some researchers speculate that the mobbing response results from the selfish herd effect[14], it has not proven yet.

Freezing The behaviour is mainly adopted by small-bodied monkeys. They rely their anti-predator behaviour on their crypticness, that is just stop moving (Miller, 2002, p. 44).

Protecting others For example predominant males in a baboon (*Papio*) troop perform this behaviour in order to protect females and infants (Busse, 1980), although the behaviour cannot be seen in all species.

Sentinel This behaviour is observed in some species. The highest-ranking individual often watches for a predator at the point where a fine view can be got from while other members are feeding (Miller, 2002, p.145). It is said that the reason why the superior male do the disadvantageous behaviours such as protecting and looking out is because most of children in the troop are possibly his kinship, though it has not been proven.

2.1.5 Leopard

In the paper leopards (*Panthera pardus*) are chosen as predators because it is said to be a key predator for many kinds of primates (e.g. Thierry et al., 2004, p. 90; Zuberbühler & Jenny, 2002). On Wikipedia the appearance of leopards is stated below:

> Leopards (*Panthera pardus*) are one of the four 'big cats' of the genus *Panthera*. (The others are the lion, tiger, and jaguar.) They range in size from 1 to almost 2 metres long, and weigh between 30 and 70 kg. Females are typically around two-thirds the size of males.
>
> Most leopards are light tan or fawn with black spots, but their coat color is highly variable. The spots tend to be smaller on the head, larger and have pale centres on the body. (Wikipedia, 2005*a*)

[14]Selfish herd hypothesis is the following: because the more members gather near to each other the less dangerous to be preyed an individual is, animals tend to flock.(Hamilton, 1971)

As for preying, their strategy can be broadly divided into two ways: hunting and ambushing. The strategies depend on their habitats. Hunting is apt to be done in the daytime, while ambushing at night. In the place where other diurnal predator, for example lions (*Panthera leo*), exist they tend to hunt in darkness instead of ambushing in daylight. They are so outstanding hunters that they do not need to surprise their preys. They stay and continue to attack in the roost of their prey for a long time. It has been observed that the victim is killed at least one hour after leopards come in the roost. (Busse, 1980)

On the contrary to the previous case, if there are not any other kinds of carnivores in the habitat leopards have tendency to ambush to prey. Probably because of the colour of their fur and its spots as well as their stealthy habit, it is difficult to detect them even in the daytime when they are in tree or bush. When a leopard detects a monkey troop during its daily trips it often hides in dense undergrowth. Its territory does not overlap other individuals at least with same sex. Accordingly it is unlikely to scramble with others for the prey while hiding. (Zuberbühler & Jenny, 2002)

2.2 Method

2.2.1 Agent

Before defining 'multi-agent', an 'agent' must be explained because multi-agent system literally consists of agents. Agent is a kind of software module used in various fields such as Artificial Intelligent (AI), Human-Computer Interfaces (HCI), Electronic Commerce (EC), and Social Simulation. Unfortunately, there is not any consensus on the definition of agent; moreover, different definitions may be used in various fields. Concerning EC mobility and ubiquitousness tend to be emphasised by reason of its distribution, while in HCI the ability to stand proxy for the user may be the most important. It goes without saying that the intelligence is essential for AI, although the meaning of intelligence somewhat ambiguous.

In spite of such diversity, autonomy is shared with all these realms as an agent's property. According to a dictionary (Hornby, 2000), the word means "the ability to act and make decisions without being controlled by anyone else". Ordinal program modules such as objects are supposed to work in the decisive environment, so that such modules need not to resolve unexpected events by themselves. All they have to do are to obey orders made by the designer in advances. On the contrary, the environment in which agents settle is indeterminate; additionally, the agents cannot ask the designer how they should react to the change every time for various reasons. The loss of time to wait for a user's order may cause a loss of a business chance. The changes may be so frequent that humans can not keep up with it. As a consequence, agent must be able to make a decision to deal with an unpredicted situation by themselves.

To realise the ability, an agent requires at least two abilities: to perceive status of its surroundings and to act with responding the perception, and what's more it must be realised that the action may affect its environment [Figure. 2-3]. As a conclusion, the highest common factor of definitions of agent is: agent is a software module which can properly react and affect

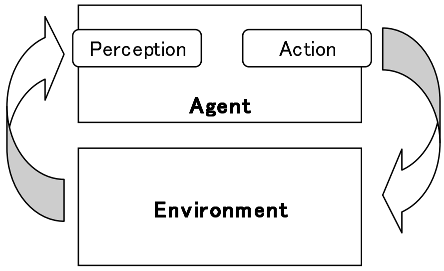


Figure 2-3: Perception and action

its unstable environment with its own decision.

2.2.2 Multiagent

In multiagent system, agents share the same environment so that agents have to cope with not only dynamic environment but also other agents. Making matters more complicated, their purposes are not always the same. In such circumstances, a certain amount of conflicts are hardly avoidable. If it happens, they manage to come to the agreement about the problem in order to avoid the impasse. Suppose that two agents facing each other have to pass their opponent. If both wait another to pass first, both must wait forever. On the contrary, if they try to pass at the same time, they may collide without regarding which side the opponent move. Even in such simple situation, the agents cannot ignore their opponent's intention. In addition, even if they aim for the same goal by the same method, it may cause the conflict over a resource. This time, suppose two agents go to the same destination on the same way. If the road is so broad that the agents can be lined up two across, agents can concentrate their own tasks. If not, they have to decide which one go first; otherwise, they chock up the road. All things considered, agents sharing the same environment are obliged to take interaction with each other, regardless of agreement or disagreement of their purposes.

Although only competition is stated so far, agents can cooperate with each other in accomplishing their common profit. Cooperation may be, however, more difficult to work well than competition. Broadly speaking, pure rivalrous system can regard as a single agent system where all other agents are regarded as a part of environment. It is significant for an agent only to manage its own task in such environment without others' pleasure. It is not true in the cooperative world. Although Sen et al. researched on the cooperation without sharing information (1994), in the most cases agents need the consensus in order to cooperate. There are lots of things to consider before cooperating: how the tasks and resources are shared, in which order shared tasks are carried out, how individual results are combined, whether a leader agent exists or not, and so on. Moreover, because the environment is not static these problems must be solved while system varying.

Although they are individually expressed it is the most difficult thing to decide when agents choose cooperating or competing with others according to the situation. In such circumstances, an agent has to worry that agents in which the agent trusts may betray it. They may occupy resources or deliberately give wrong information. Of course, the agent can deceive them on the contrary. The theory to handle such system is known as 'game theory'. More precisely 'Repeated Prisoner's Dilemma Game' completely agree with the situation and the tactics called 'tit for tat' is corroborated to be the most effective in the game (Wooldridge, 2002, pp. 119-122). However, because the game assumes only two agents, the tactics is not always the best in multiagent system (hereafter MAS).

Microscopic agent interaction has been stated so far. Actually a large number of agents are deeply interwoven with each other in MAS. Such system is called 'Complex System'. Despite of the publicity, there is not a decisive definition of the term; moreover, many people define it in many, further contradict, ways. Followings are the examples:

- "A complex system is a highly structured system, which shows structure with variations"
- "A complex system is one whose evolution is very sensitive to initial conditions or to small perturbations, one in which the number of independent interacting components is large, or one in which there are multiple pathways by which the system can evolve"
- "A complex system is one that by design or function or both is difficult to understand and verify"
- "A complex system is one in which there are multiple interactions between many different components"
- "Complex systems are systems in process that constantly evolve and unfold over time"

(All items are quoted from *Science Vol. 284. No. 5411*, 1999). Before the advent of complex system, the mainstream scientific way is 'divide and conquer' and it is considered to be working well. Taking a complex system into consideration, the simplification does not succeed because the value of complex system is found not in components but in their interaction. Examples of the complex system are turbulent flows and the brain (Vicsek, 2002). A notable thing is that MAS may be able to reproduce such a system as it is on a computer.

2.2.3 Agent-Based Modelling

Some people are doubtful of utility of computer simulation, especially agent-based modelling (hereafter ABM), because it seems to lack enough foundation and to be oversimplified. However, for example a mathematician who strictly makes a point of formulae may feel ambiguous statistical way adopted by a sociologist, while a practitioner may regard such formula as just an armchair theory. The validity of a method is inclined to be evaluated differently according to the background of evaluators.

To judge ABM, it might be better to think how to use of it rather than to wonder whether it is useful or not. Axelrod wrote "Simulation in general, and ABM in particular, is a third way of doing science in addition to deduction and induction" (2005). It allows us to alternately travel between them. A hypothesis is retrieved by an inductive way, then the hypothesis is deductively examined with ABM; besides, a new or revised hypothesis can be distilled from the result of ABM, and so on. The repetition can iteratively approximate the hypothesis to the truth.

It is unlikely for ABM to prove a theorem itself; however, data can be generated in the suitable form to analyse so that it can help to prove. Some realms suited for neither pure induction nor pure deduction is fit for this way. One of them is a complex system. As it is mentioned above, it is difficult to induct the nature of the system from emerged phenomenon because it highly depends on *interactions* among each constitutional elements. ABM is suitable to handle such domain in which interactions are made much of. Typical examples are emergence of human society, policy modelling and developing, and others (Wooldridge, 2002, pp. 259-263).

One of the most famous outcomes that the ABM is applied to ecological world is done by Craig Reynolds (1987). He proved that the characteristics of aggregation, namely flocks, herds, or schools, of animals can emerge from short-sighted individual behaviours based on only three rules without being supervised. This leads that ABM is useful to analyse the animal behaviour although some people including Raynolds calls such method, where the society is modelled by interactions between near-sighted agents, Individual-Based Modelling.

2.2.4 Hemelrijk's Model

Hemelrijk's model, called 'DomWorld', is a well known Individual-Based Model representing a primate society. As you might see from the abbreviation 'Dom', she modelled the society with paying attention mostly to dominance interactions. Roughly speaking, agents have tendency to head for another agent in DomWorld. However, once another agent invades its personal space, the agent tries to perform competitive interaction with the invader in the case that the agent is more dominant. When the interaction is finished, the dominance value is updated according to the result. Lastly the winner chases the loser while the loser escapes from the winer and turn at a certain angles in order to avoid continual interactions by the same pair. The algorithm is illustrated in Figure 2-4.

The way to update `Dom` is explained in detail because it is the kernel of DomWorld. At first a monkey invaded its personal space by other anticipates the result of the contest, in other words, weighs up their `Doms`. If it is less dominant than the invader, it just ignores the intrusion because it may lose the dominance interaction. Otherwise it attacks the intruder and win or loss is decided by Equation 2.1. '$w = 1$' means the attacker wins. Accordingly the dominant one probably wins but it is still possible to lose.

$$w_i = \begin{cases} 1 & \dfrac{DOM_i}{DOM_i + DOM_j} > RND(0,1) \\ 0 & else \end{cases} \tag{2.1}$$

As a result, winner's `Dom` is strengthened and loser's one is weakened. Precisely, `Doms` of the participants are updated by Equations 2.2, 2.3. The more differential their `Doms` are, the wider

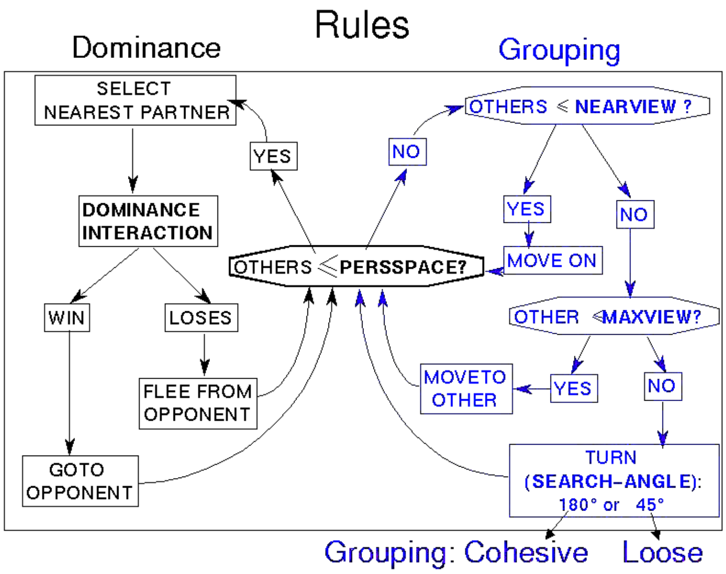


Figure 2-4: Flow chart for the behavioural rules of agents (Hemelrijk, 2001, Figure 1.)

their changes are.

$$DOM_i := DOM_i + \left(w_i - \frac{DOM_i}{DOM_i + DOM_j} \right) \times STEPDOM \tag{2.2}$$

$$DOM_j := DOM_j - \left(w_i - \frac{DOM_i}{DOM_i + DOM_j} \right) \times STEPDOM \tag{2.3}$$

Hemelrijk has demonstrated the following aspects of primate society using this simple model (2000a).

- Spatial centrality of dominants. The more dominant individuals tend to occupy the more central position of the troop.
- The emergence of reciprocation of support in conflicts. Because a beaten agent must flee without knowing other agents, it tends to intrude others personal space and be challenged continually.
- Decrease of aggression. Lower ranking agents are turned to the fringe of the troop then the total number of aggressive interactions decreases.

2.3 Tool

2.3.1 Multiagent Simulator

As stated in the above, multiagent simulation can be applied for a variety of fields; however, developing the application for MAS is far from easy. The primary problem is performance. Lots of repetitions of simulation with many agents are usually required to achieve a stable result (Luke et al., 2004) and it can easily exhaust computer resources, namely CPU cycle and memory. Scheduling of agents is another problem. Some known problems such as cellular automata (CA) require the model status being updated synchronously (Wolfram, 1983), others not. Apart from driving a model, monitoring is another difficulty. It introduces additional complexity into the system and consumes extra resources. Moreover visualisation is not only a feature which should not be ignored but also one of chief purposes of MAS because its behaviour are demanding to imagine without observation owing to its complexity (e.g. Murakami et al., 2002).

To solve these and other problems, a variety of frameworks are offered. Although three of their characteristics are briefly introduced below in order to survey the general feature of MAS tools, none of them is adopted for the dissertation. Both the reason and the solution are stated in the next section.

Swarm: This is the most historic MAS tool so that it affects many other MAS tools. It is characterised by being written in Objective-C. Although swarm model can be implemented only by Objective-C in the beginning, Java can be used now. From the viewpoint of framework, the characteristic is the existence of hierarchical swarm, which is a set of agents, schedule, and event. In other words, the field where agents act can be handled as an agent. Such recursive definition cannot be seen in other MAS frameworks. (Minar et al., 1996)

NetLogo: As Logo language aims for teaching (Logo Foundation, 2000), NetLogo is suitable to learn and teach ABM. The word 'Net' in 'NetLogo' means that it is enforced functions for networking and the extension is supposed to be used in a lecture room for one lecturer to manage all students. Easiness of mastering is, however, beneficial for research especially by not-computer scientist. As for performance, it is unfortunately not very good because not only the environment is written in Java but also the user program is executed by interpreter. However, these two characteristics have some advantages. Java allows executing on multi-platform and interpreter enables to revise models iteratively. (Wilensky, 1999)

MASON: MASON is a multiagent simulation library written in Java. Special feature of it is in its "hackability". The developers decide to keep the simulator core as small as possible in order to realise the high performance, which is one of their motivations for development. In stead of the simplicity, it can be easily modified. An example of easiness of extension is the function drawing charts and graphics which is achieved by combining with external library, JFreeChart (Gilbert & Morgner, 2005). Although visualisation tools are not included in the simple core, rich libraries in 2D and 3D are offered separately from it. To add to the separation of modules, the developers suggest that a MASON user creates a model in two stages: the first model without GUI and the second with. (Luke et al., 2004)

2.3.2 Squeak

This is quite different from above three. In fact, this is not a multiagent simulator but a reborn Smalltalk (Ingalls et al., 1997). However, compatibility between a dynamic typing object-oriented language and multiagent simulator has been proven by Objective-C and Swarm. Moreover Smalltalk has additional advantage for multiagent simulation. The word 'Smalltalk' is actually used in three different meanings: development environment, class library, and object-oriented language (see Figure 2-5).

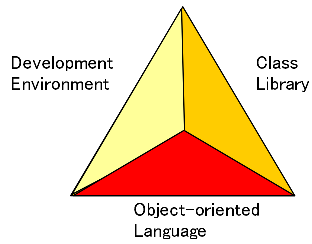


Figure 2-5: Three Elements of Smalltalk System (Lewis, 1995, ch.3)

The class library allows users to handle Smalltalk itself as a kind of a framework. Most functions of Smalltalk are achieved not by defined grammar but by the class library, which a programmer can alter. The IDE enable to peek inside of active objects. Accordingly, every object can individually talk with each other by message passing because of object-oriented, the conversations can be observed through the IDE, and users can modify these functions thanks to the offered source code (i.e. class library). These facts might mean Smalltalk has already been a simple multiagent simulator.

In addition, there is an interesting application pre-installed in Squeak; it is called SqueakToy or eToy[15]. Although it is just a kind of graphical programming environment, it is so functional that it may be regarded as a MAS toolkit. For example, elementary students were able to create the AIDS contagion simulation using SqueakToy (Kay, 2001).

[15]Although eToy is often used it is a trademark of an irrelevant product to Squeak so that there are some people to avoid using it.

Part II

Development

Chapter 3

Principles

3.1 Premise

The framework addressed in the dissertation is not so rigid as usual frameworks that a user can modify almost all place if necessary. It should be called not framework but seedwork (Fowler, 2003), although 'framework' is chosen as the classification in the paper because of the publicity of the word.

Roughly speaking, a framework is what restricts functions of a programming language on which the framework is implemented because it hides places which do not mean to be changed as well as illuminates places for extension. The limitation makes it easy for users to concentrate on the only extension points, so that it is usually recognised as a proper feature. The separation between hiding and illuminating is known as 'Open-Close Principle', which is one of the most important principles for object-oriented programming (Meyer, 2000). It must be effective, provided that the extension points are clear in advance.

At the present time, there is only Hemelrijk's DomWorld Model (Hemelrijk, 2000*a*), which is acknowledged as the simulation model that can represent monkeys' hierarchical society well; however, the fact does not mean that the framework for the dissertation needs to handle only the model. On the contrary, the framework must be able to deal with various kinds of models which anyone has never thought up yet.

Accordingly, as long as taking the future application into consideration, it is required that the framework developed in the dissertation must restrain the power of programming language as little as possible and allow a user modifying all parts of the application.

3.2 Automation

As stated in Section 2.2.3, ABM is suitable for simulation of undecidable environment. In other words, different results can be observed even if each experiment is conducted in the same condition. In that case, same experiments must be repeated many times and their results should be handled in statistical way. It is consequently desirable that the framework can automatically carry out not only one sequence of an experiment but also repetition of the sequences composed with setting up, executing, recording its result, and tearing down.

Although the automatic experiment is beneficial there is one key characteristics of MAS which should not be neglected; the behaviour of MAS is so complex that the visualisation is one of main purpose for MAS framework (e.g. Murakami et al., 2002). Even if all series of experiments can be performed automatically, it is meaningless if a user has to observe all the time they are executing. In order to solve the problem, the framework must be able to reproduce all experiments if it is necessary. When examiners find something strange or interesting in a record of an experiment, they can observe actually what happens at that time through the function of playback.

3.3 Easiness To Add New Experiment

Because of unpredictability of models which will be thought of, it is uncertain what kind of experiments are required to verify their properness. Accordingly it is essential to be easy to create various kinds of experiments.

Although there are a lot of functions which can characterise an experiment, the following functions are aimed in the dissertation. The framework must allow experimenters to easily set up the specific initial condition of world. For example necessary types of agents and a starting status for each depend on experiments. Various worlds should be easily constructed in the framework. The collected data naturally rely on what the experimenter want to know so that it is important to offer users an easy way to configure which data is collected and when. Lastly a proper format of a result is dependent on types of the data. It is desirable for users to be provided various view of the result.

3.4 Design Criteria

All requirements mentioned in above sections are summarised in the followings:

- The framework must utilise the power of the programming language on which the framework itself is implemented as much as possible.
- The framework must not restrict any function of the language if possible.
- The framework must be able automatically not only to perform an experiment but also to repeat the experiment.
- New experiment must be easy to be implemented on the framework.

Chapter 4

Design

4.1 Programming Language

The framework is developed on Squeak (Ingalls et al., 1997), which is one of implementations of Smalltalk. It is because of compatibility between Smalltalk and some feature of the framework described in Section 3.4:

- The framework must utilise the power of the programming language on which the framework itself is implemented as much as possible.
- The framework must not restrict any function of the language if possible.

In other words, Smalltalk can allows to develop the framework which does not detract any powers of the language.

As expressed in Section 2.3.2, 'Smalltalk' does not mean only the grammar of a programming language. It includes a class library, a development environment, a runtime environment, as well as the grammar. A notable aspect for the case is its class library. It is so massive that some functions which other languages define as a part of those grammars are implemented in the library. For an outstanding example, the grammar of Smalltalk do not define two control structures, namely condition and iteration, which are considered two of three essential control structures for all programming languages. In the case of Smalltalk they are provided with its class library. To put it another way, Smalltalk itself can be regarded as a framework consisting of its libraries.

Additionally the Smalltalk libraries are completely open to all developers. They are allowed to change Smalltalk core class libraries as they want. For example, a developer even can add new method on `Object` class, which is the root class of all other classes except for `ProtoObject` class. By doing so, the message can be handled by all objects because all messages which cannot be understood by an object is delegated to its super class and the hierarchy ultimately reaches the `Object` class; besides, the change becomes valid for all objects (even those of already instantiated) as soon as it is accepted by the system. In most of other object-oriented languages

Layer N
...
Layer J
Layer J-1
...
Layer 1

Table 4.1: Layers

it is impossible to change the whole classes in such way. Thanks to the feature, it is often seen that each developer has her/his own Smalltalk which has different core library each other. Although the characteristics may not be suitable for commercial products, it is optimum for the aim of the dissertation; developing the framework which can take maximum advantage of the programming language.

From the facts mentioned above, the Smalltalk can possibly be formed into the MAS simulator for the experiments as it still remains to be Smalltalk if the development succeeds.

4.2 Architecture: Layered Approach

Layered approach is often adopted in order to realise maintainability, reusability and so on in various domains (e.g. Stevens, 1994, ch.1). Buschmann et al. organised many software patterns in their books in sophisticated way and stated about the layered pattern as following: "The Layers architectural pattern helps to structure applications that can be decomposed into groups of subtasks in which each group of subtasks is at a particular level of abstraction." (1996).

4.2.1 Dividing Into Layers

Buschmann et al. described the process to divide system into layers as following:

> Start at the lowest level of abstraction - call it Layer 1. This is the base of your system. Work your way up the abstraction ladder by putting Layer J on top of Layer J-1 until you reach the top level of functionality - call it Layer N [see Table 4.1] (1996).

As regards the dissertation, the most abstract layer is Squeak itself while the most functional layer is the layer where each experiment is performed. The problem is how to connect the gap between them by layers.

Squeak has a framework to construct GUI, which is called Morphic Framework. Although MVC is a well-known mechanism for building GUI on Smalltalk, Morph is based on a bit different idea and makes it easier to implement animated objects than MVC. The framework is appropriate for the base of the development. Because Hemelrijk's DomWorld derives from what is called Individual-based Modelling (hereafter IBM) (Hemelrijk, 1999*b*) the layer responsible for IBM aparting from DomWorld layer is worth to be constructed. Then taking advantage of the layer the DomWorld layer is built. A plain experiment layer is created not on DomWorld layer but directly on the IBM layer owing to the fact that the model based on any other theory than DomWorld may be intended in the future. The layer specialised for the experiment based on DomWorld is created on the top of both experiment layer and DomWorld layer. As a conclusion the architecture of the framework aimed for the dissertation becomes seen in Figure 4-1.

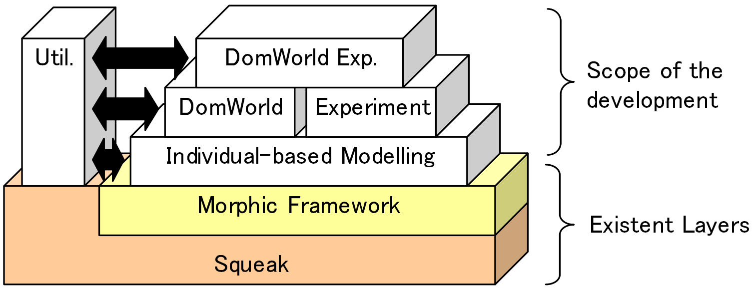


Figure 4-1: Architecture

4.2.2 Description about Each Layer

The brief description about the responsibility of each layer is offered respectively below.

Individual-based Modelling Layer This is the most fundamental layer; more specifically, it is responsible for displaying and scheduling all agents, recording and reporting results of experiments, and managing the user interface.

IBM Experiment Layer Although the main scope of this dissertation is only DomWorld, it is likely that a completely different model will be considered in the future. This layer offers the means to construct an experiment directly on the IBM layer, namely regardless of DomWorld, and the base of other experiment layer in higher layer.

DomWorld Layer This layer constructs Hemelrijk's DomWorld by utilising IBM layer. To be specific, it provides DomWorld monkey agents which can play dominance interaction and its predator agent although the predator does not appear in the original DomWorld.

DomWorld Experiment Layer Both IBM Experiment layer and DomWorld layer are utilised for the layer. All experiments for the dissertation are built on the layer.

4.3 User Interface

Concerning the user interface, the principle of the framework for the experiments is simplicity. It is preferable that ordinary experiments can be done by pushing only a few buttons. The experiment framework is based on the same idea of xUnit testing tools (Beck, 2005) because an experiment and a unit testing can be regarded as similar from the viewpoint to make sure certain facts. The ideas are the followings:

- Both setting up and tearing down of an experiment are automatically done and all an experimenter has to do are only to start an experiment and to check the result.
- A series of experiments can be handled in the same way as single experiment. That is to say, some experiments can be started by only one action as expressed in the previous item.

Although the simplicity of usage looks contrary to the principle that the framework must be able to use full power of a programming language, which is stated in Section 3.1, these requests do not conflict with each other on Smalltalk because the environment for development and for runtime are integrated on it. Even if the tool is made as simple as possible, all system tools such as the notifier, the system browser and so on are still available when necessary.

As for development tools, one of the most useful tools in Smalltalk is the inspector, which allows users sending a message to an existing object as well as peeping and modifying its properties. Because everything under the Smalltalk are realised by message passing users can do everything in the inspector. It is even possible to add new method on an existing class. Although the inspector usually should be called in some way to utilise it the simulator makes its own inspector available at all times.

4.4 Other features

Among Smalltalk implementations, Squeak has particularly strength in its multimedia aspects. For example it has the following libraries at default setting though the list depends on its version.

- Morph (2D Graphics)
- SqueakToy (2D Scripting)
- Balloon 3D (3D Graphics)
- Wonderland (3D Scripting)
- Score Player, Sound Recorder, Wave Editor, and so on (Sound)
- Speaker man (Speech)

If it can be afforded to do, better visualisation may be offered by taking advantage of some of them, but it is not a rigid requirement.

Chapter 5

Implementation

The implementation of the framework for the dissertation is named BoidWorld. 'Boids' means the generic simulated flocking creatures and is introduced by Reynolds for the first time (1987). The reason why the name is chosen is because it sets agents' spatial perception above their interaction with environment. In addition it seems appropriate for the most abstract expression of DomWorld. To be specific the grouping rules [see Figure 2-4] is almost the idea of Boids itself. Accordingly the substance of the layer called IBM in Section 4.2.1 is the BoidWorld. DomWorld is built on the BoidWorld and mainly concentrates on the dominance interaction between monkeys.

In this chapter, the detail of the whole BoidWorld framework (including DomWorld) is explained along the categories, which are means to organise a group of correlative classes in Smalltalk.

5.1 Overview

The class diagram where all classes contained in the system is offered in Figure 5-1, although only major relationships are drawn and all methods and fields are omitted.

As seen in Figure 5-1 categories, which are represented by tagged boxes (i.e. UML packages), do not correspond exactly with layers in Figure 4-1. Boid-Kernel category includes both Individual-Based Modelling layer and Experiment layer, as well as there are not any corresponding layers to Boid-Behaviors category or Boid-Tiles category. One of the reasons is that the system is divided into categories according to OCP (Meyer, 2000) from the point of view of implementation (see also Section 3.1). For example, although all classes in Boid-Behavior category normally suit for Boid-Kernel category or Boid-DomWorld category, these categories are separated because Boid-Behavior category is apt to be added new classes much more than other two categories. On the contrary both Individual-Based Modelling layer and Experiment layer are entirely fixed and related each other to be separated.

Note that the class diagrams in the section address not design but implementation. Some of inheritances of interface are not shown on these diagrams because Smalltalk is dynamic typing

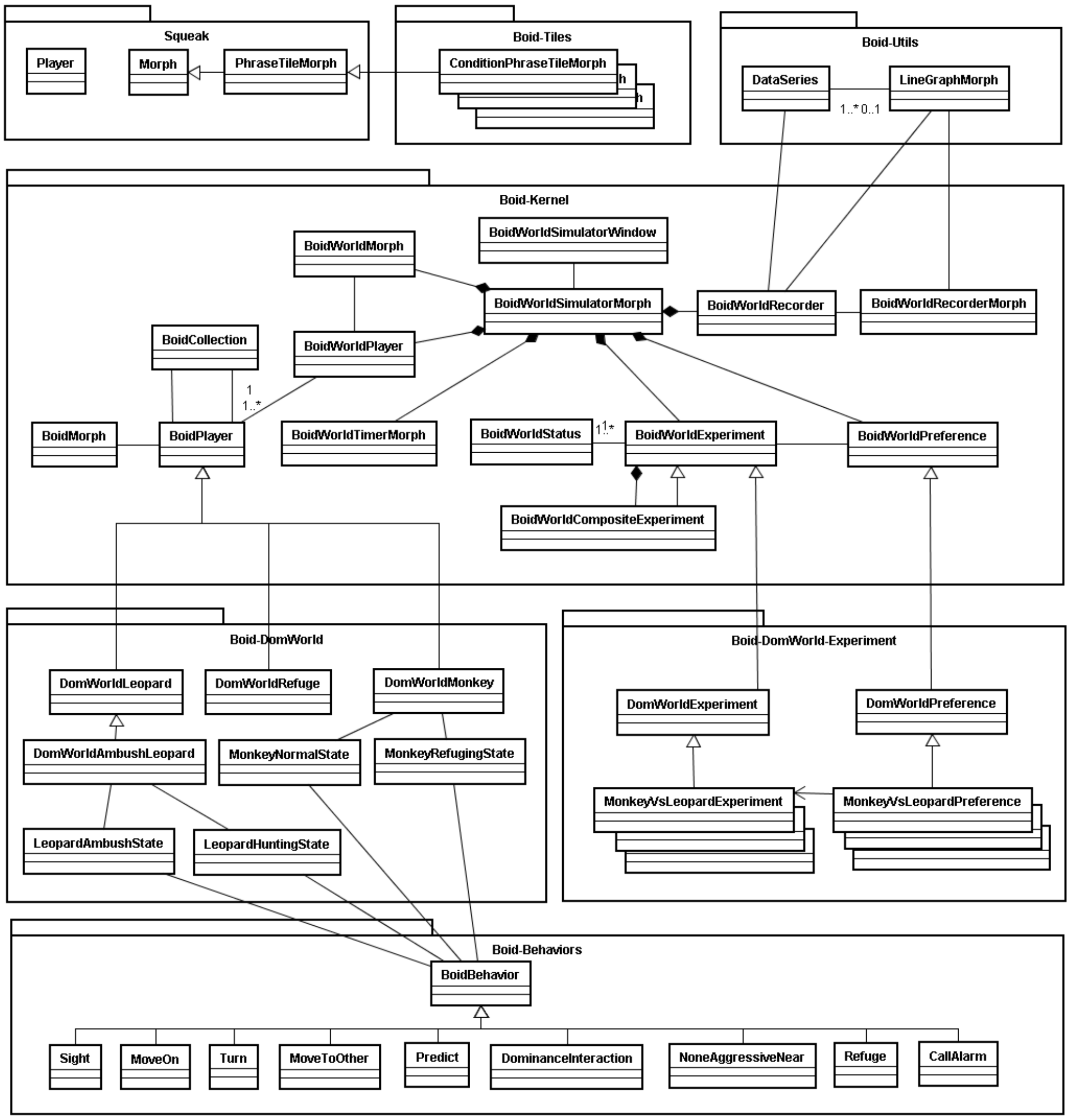


Figure 5-1: Class Diagram

language.

5.2 Boid-Kernel Category: Individual-Based Modelling And Experiment Layer

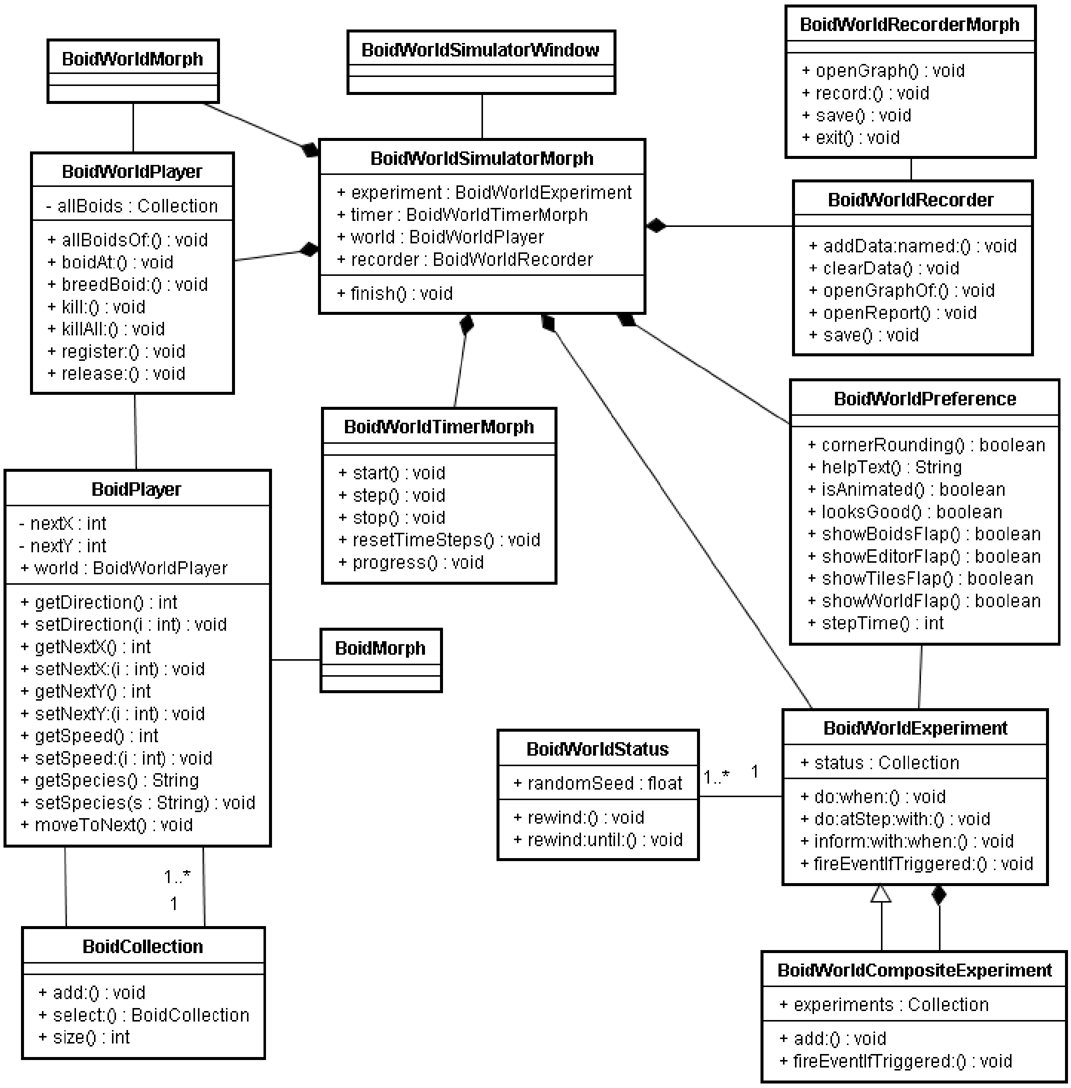


Figure 5-2: Class Diagram of Boid-Kernel Category

This is the most fundamental category in the system, so that most members will be explained afterward in detail. In fact, the category is sufficient to develop an individual-based simulation. Users can do all things they need by using classes only in the category; that is, they can create new boid which has its own appearance and features, manage (i.e. peep the state, change the state and delete) existent boids, control timer (scheduler), and so on. Accordingly, it is recommended to do prototyping by using only the kernel classes before adding new classes such as those in DomWorld category. Unfortunately prototyping using BoidWorld framework is a bit strayed from the point of the dissertation so that it is omitted from the body. Please see Appendix A if necessary.

BoidWorldSimulatorMorph There are three starting points in the system and this is one of them. Other two are `BoidWorldSimulatorWindow` and `BoidWorldMorph`; `BoidWorldSimulatorWindow` is just a wrapper to put `BoidWorldSimulatorMorph` into a Squeak system window, and `BoidWorldMorph` is obsolete as a starting point although it still works. `BoidWorldSimulatorMorph` is, therefore, the primary starting point. The most basic command to start the system is following:

```
| simulator |
simulator := BoidWorldSimulatorMorph new.
simulator openInWorld.
```

From the functional view, the class aggregates most of important classes and the classes communicate each other via the class, as well as it is a front-end where a user operates the system.

BoidWorldPlayer and BoidPlayer These two are the most essential classes in the system as their names show. `Player` class is positioned as Model class of `Morph` class in Morphic Framework, which is the base mechanism to construct the GUI of the framework; hence, each class has a corresponding `Morph` class as its View class. `BoidWorldMorph` and `BoidMorph` are, however, much less important than their Players. The entire Morphs do are just overwriting some method of the super class in order to change some default behaviours and delegating most of required messages to the correlated Players.

Describing based on Figure 2-3, `BoidPlayer` is Agent whilst `BoidWorldPlayer` is Environment. `BoidPlayer` is perceptive about statuses of `BoidWorldPlayer` and acts according to the perception. The reason why they are not called Agent nor Environment is that the perception and the action are mostly regulated to spatial attributes and the tendency is characteristic seen in Boids (Reynolds, 1987).

BoidWorldPreference and BoidWorldExperiment The two are base classes to add new experiments. To be specific, `Preference` classes set the configuration of the system such as the appearance, the contents of the menu, the frame rate, and so on. On the other hand, the main responsibility of `Experiment` classes is to introduce special events triggered by particular situation into the World. For example, it can define following events:

- When the number of time steps reaches a certain number, all boids stop moving and the report about the result of the experiment is opened.
- When a monkey does vigilant action, the characteristics of the action are recorded on the system.

- When a monkey calls alarm for a predator, all monkeys start fleeing.

As seen in above examples, events defined by `Experiment` class are not restricted only an experiment stuff (e.g. the first and second items). Rather, it can introduce an event which changes a behaviour of an agent. Such an action selection is usually implemented in the agent class and it is of course possible in the framework; however, there is, unfortunately not any specific mechanism which makes it easy to change behaviours of an agent in the current implementation of the framework. Accordingly, whenever an experimenter needs new behaviour s/he has to create new agent class no matter how trivial the behaviour is. Under such circumstances, it is a valid alternative to implement the behaviour in an `Experiment` class in order to collect correlated changes in one place.

Though there are a lot of things `Preference` classes and `Experiment` classes can do, `BoidWorldPreference` and `BoidWorldExperiment` do almost nothing in fact. Most of their methods are implemented as simple as possible, so that experimenters need to modify them on their subclasses. How to create new experiment is stated in Section 5.4.1.

The example to start the BoidWorld which uses a particular preference is following:

```
| simulator preference |
preference := DomWorldPreference new.
simulator := BoidWorldSimulatorMorph newWith: preference.
simulator openInWorld.
```

BoidWorldTimerMorph This class invokes certain scripts of all Boids in the same world as the timer class at given intervals. There are two way to repeat invoking at regular intervals; one is the way to utilise predefined event loop in Morphic Framework and another is to employ its own worker thread. Both have advantages and disadvantages. The former allows synchronised changing statuses of boids with updating the display; for instance, when a boid move to a different position, means their internal x and y values are changed, the boid is immediately displayed at the point. The morphic event loop is, however, limited its performance because the loop is shared by all visual objects in Squeak so that it is not suitable for resource consuming process. The feature of the latter, its own worker thread, is the opposite. It may cause jerky animation, whilst it can take advantage of full of CPU power. According to the characteristics it is recommended that the morphic event loop is chosen for prototyping and the worker thread is chosen for actual experimenting. It is easy to switch them.

Specific sequence of message passing to drive the world of boids is explained in the next section.

5.2.1 Sequence

A sequence diagram explaining which messages are called at each time step is available in Figure 5-3. Although the diagram expresses the case of the worker thread, most of it is valid in the case of the morphic event loop because the loop regularly calls the `step` method of `BoidWorldTimerMorph` too.

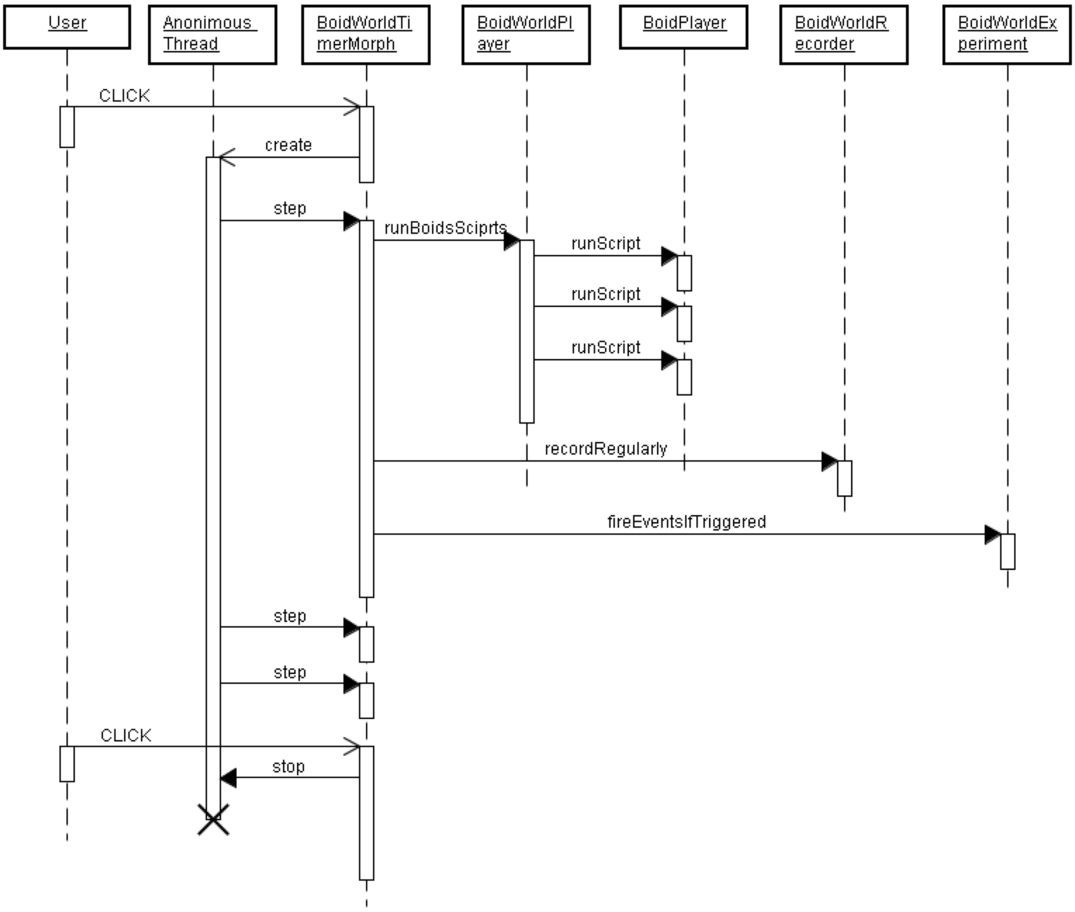


Figure 5-3: Sequence

As seen in the sequence diagram three methods are called in `BoidWorldTimerMorph#step` method in tern. In brief, all boids are moved to next position based on a given rule correlating perception and action at first. Then the regular data about the world and boids are collected. Finally, all event triggers in the corresponding `Experiment` instance are checked and fired if necessary. Any specific process is executed at the point.

5.2.2 How To Add New World

In Boid-Kernel category, there are four extension points, namely classes which are prepared to be inherited in order to bring new features in the system. They are:

- BoidWorldPlayer
- BoidPlayer
- BoidWorldPreference
- BoidWorldExperiment

Which of those of subclasses are created depends on how complex the new world is; however, it is rarely needed to make all of them. The last two are extended for mainly creating not a specified world but new experiments so that they are explained in Section 5.4.1 (How To Add New Experiment). Motivation to extend the first two classes is described just below.

BoidWorldPlayer If the world intended by an experimenter holds static and uneven properties such as potential energy the subclass of `BoidWorldPlayer` is good place to extend. This class is not extended for the dissertation.

BoidPlayer When a boid having special attributes or/and behaviours is required, a subclass of the class should be implemented. Almost whenever an experimenter needs new world, the class should be extended.

5.3 Boid-DomWorld Category: DomWorld Layer

In this category, there are three subclasses of BoidPlayer class, which characterise DomWorld. Among those three, `DomWorldMonkey` is of primary importance because all features of DomWorld (see Figure 2-4) are implemented in it. Other two subclasses are newly introduced for the dissertation and behave a minimum.

These players should be able to change their way of thinking according to their circumstances for example a leopard finding a monkey and a monkey detecting a leopard so that the State Pattern proposed Gamma et al. (1995) is adopted. Briefly explaining a state class holds all state-specific behaviours and the owner of the state instance delegates all processes depending on a state to the state instance. By doing so, the transfer of internal states can be represented by exchanging state instances. The classes suffixed ‘State’ stand for the pattern.

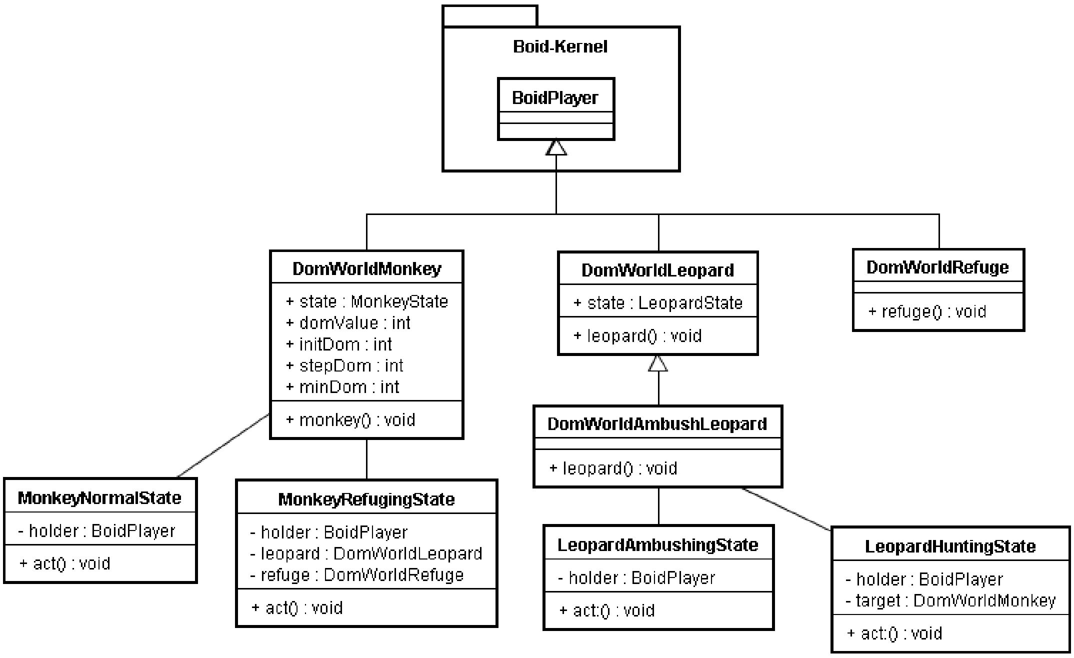


Figure 5-4: Class Diagram of Boid-DomWorld Category

5.4 Boid-DomWorld-Experiment Category: DomWorld Experiment Layer

The category contains two plain classes which are prepared to be utilised as a super class for particular experiments. They are `DomWorldPreference` and `DomWorldExperiment`. The main task of `DomWorldPreference` is to make the appearance of the world poorer in order to improve the performance of experiments, while `DomWorldExperiment` is created for future enhancement and do nothing at the point.

All other classes are for particular experiments. Although some of experiments are related each other, they have no inherited relationship among them. Most of them are created not by inheritance but by copy & paste. The reason is that each experiment should be completely independent each other and experiments should be remained of their condition that they are executed in order to be able to reproduce the experiments.

5.4.1 How To Add New Experiment

Four classes are listed as extension points of BoidWorld in Section 5.2.2 although only two of them have explained so far. As can be expected, other two classes, `BoidWorldPreference` and `BoidWorldExperiment`, are mainly used to add new experiments.

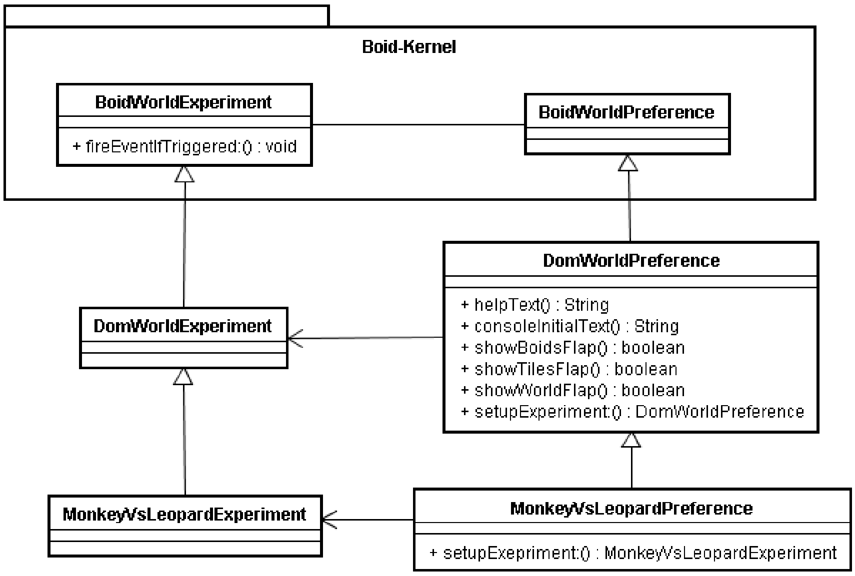


Figure 5-5: Class Diagram of Boid-DomWorld-Experiment Category

BoidWorldPreference From the view point of producing new experiment, the leading responsibility of the class is to be a factory of an experiment, that is, to set up a plain Experiment with necessary triggers and to pass it to the system.

BoidWorldExperiment This class is so flexible that any trigger and event block[1] can be scheduled to be executed. For example, if an experimenter needs to stop an experiment and open a graph of the result when particular time steps are consumed s/he can write as following:

```
| particularTimeSteps experiment |
particularTimeSteps = 1000.
experiment := BoidWorldExperiment new.
experiment
    do: [:world |
        world timer stop.
        world result openGraph.
    ]
    when: [:world |
        world timer timeSteps = particularTimeSteps.
    ].
```

Accordingly subclasses of the class may not be necessary in most cases. All subclasses of the class seen in the dissertation are introduced to make the codes easy to read. Because

[1]A block is a chunk of Smalltalk expressions, which is inspired by lambda function of Lisp.

Experiment instance is passed to the system by Preference instance, whenever new Experiment class is implemented new Preference must be required and all they do are only setting themselves up in `initialize` method.

5.5 Other Categories: Utility Layer

Boid-Behavior Category This category contains many behaviours employed by `BoidPlayer` class and its subclasses. Although these behaviours can be implemented as methods of `Player` class, they are made separated because of preparation for a future extension (see Chapter 11).

Boid-Utils Category At the point, there are only two classes in the category: `LineGraphMorph` and `DataSeries`. As it can be expected from the names, their task is to display line graphs. `BoidWorldRecorder` and `BodiWorldRecorderMorph` highly depend on these Morphs and any combination of recorded data can be displayed on a line graph.

Boid-Tiles Category In Squeak there is a visual programming framework what is called SqueakToy (or eToy), where programming is done by placing tiles which stand for fragments of Smalltalk expression (see Figure 5-6). It is recommended to prototype new model in the

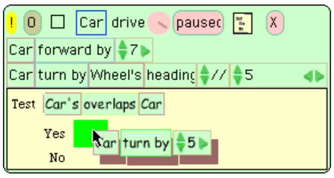


Figure 5-6: An Example of SqueakToy Programming

`BoidWorld` using the SqueakToy and this category contains convenient tiles for constructing a prototype. To know in more detail about it, please see Appendix A.

Chapter 6

User Interface

6.1 Features of Main Morphs and Basic Procedure

Based on the UI design criteria in Section 4.3, the user interface is quite simple from the view point of the tool for experiments [1]. A normal procedure for carrying out an experiment consists of only two steps: to click a corresponding prepare button and then to click a timer button to start the experiment (refer to Figure 6-1).

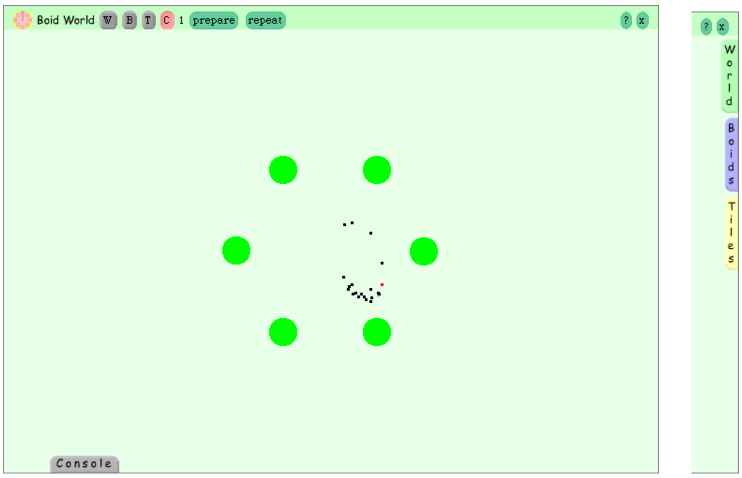


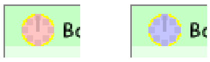
Figure 6-1: Typical screen for an experiment

The number of 'prepare' buttons depends on the installed `Preference` class. If more than one experiment can be executed on the setting, the same number of buttons are displayed. In the case of the figure, two prepare buttons, respectively named 'prepare' and 'repeat'.

The timer button is the leftmost circular one and is used both to display the status whether the world is driven or stopped and to toggle the status. Clicking one of prepare buttons results

[1] As a tool for prototyping a model, it is a bit complicated. See Appendix A.

in setting up the world but usually do not start ticking so that a user needs to click the timer button explicitly. The statuses can be distinguished by its colour (see Figure 6-2) and animation. When the world is working the hand of the timer rotates. It may feel strange to change its appearance according to the status because it must be obvious whether the world is being driven or not. However, the framework allows stopping updating the display while an experiment is executed in order to improve the performance, so that the variation of the colour is useful.



(a) stopping (b) working

Figure 6-2: Timer Button

Four buttons, labeled 'W', 'B', 'T' and 'C', between the timer button and prepare buttons have little to do with an experiment. They provide the function to hide unnecessary tabs. In fact, only 'C'onsole tab is important for an experiment and others are usually hidden (see Figure 6-1). To know about the three in detail, see Appendix A.

As soon as the experiment finishes `ReportMorph` is opened in the world and the experimenter can handle the result through the Morph. Some of the closings of experiments are hard to tell by just seeing but the emergence of a report can notify an experimenter of the closing. In addition its lifetime has nothing to do with that of the framework, so that it is possible not only to start next experiment but also to finish the framework with keeping the report open.

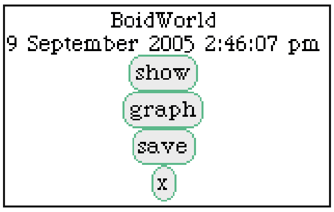


Figure 6-3: ReportMorph

There are three buttons on the report: 'show', 'graph' and 'save'. When 'show' button is clicked, the result is displayed on Transcript window, which is like so-called STDOUT in other popular languages. In most cases it is not realistic because the result is too large to be displayed on a screen. Therefore the next button is more useful to check the result. As can be expected from its name, the 'graph' button opens a line graph of the result. What kind of data is displayed depends on the experiment. Some examples of graphs can be seen in Figure 6-4. When the result seems valid, then the user clicks 'save' button to store it in a file and clicks 'x' to close the report and derived graphs.

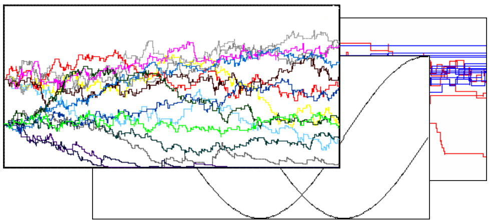


Figure 6-4: Line Graphs

6.2 Console Tab

Although the basic procedure is such simple as stated in the previous section there must be a moment when an experimenter needs to do more complicated survey. Console Tab, which is in the bottom of the application, offers the means to do it (see Figure 6-5). On the console

Figure 6-5: Console Tab

every Smalltalk expressions can be evaluated in the context of the simulator[2]. Therefore any special investigation is practicable on it. For an extreme example, it is even possible to define new boid class and put it on the world in the console, although it is too complex and useless actually to do it. A practical example is provided in next section.

6.3 Inspector

It is more convenient to inspect not only the simulator but also any other objects. It is of course possible in usual way of Smalltalk, namely some clicks and choice from menus; moreover, the console tab can make it easy. When a user types either below commands on the console tab corresponding inspector(s) are open in the world.

```
''open an inspector for the first boid''
world allBoids first inspect.

''open each inspector for all boids''
world allBoids do: [:b| b inspect].
```

[2]'in the context of the simulator' means that `self` refers to the simulator instance and all instance variables of the instance can be accessed by only their name.

The screenshot of the inspector is shown in Figure 6-6. Although the inspector is pre-installed on Smalltalk and it is not something developed for the dissertation, it is worth to explain in a bit detail because it is indispensable for development and experiment with Smalltalk. It consists of three panes. Top-left one shows a list of all names of instance variables of the target instance and the value of chosen variable in the list is displayed on top-right pane. The inspector in Figure 6-6 is peeking a DomWorld monkey so that a user can read its `domValue` is 8.0. In addition, a user can also change the value on the top-right pane. If the user wants to make the monkey the most dominant individual s/he allows to set the `domValue` 20.0 or more. The bottom area has the same role as the console tab. In other words, an examiner can evaluate any Smalltalk expression on the pane in the context of the target instance.

Figure 6-6: Inspector For BoidPlayer

6.4 Another Appearance

The framework offers the way to change its appearance easily. Although a simpler one is preferable in many cases because of its quickness, a finer appearance may be desirable for example when it is demonstrated in public. The finer version of DomWorld is shown in Figure 6-7.

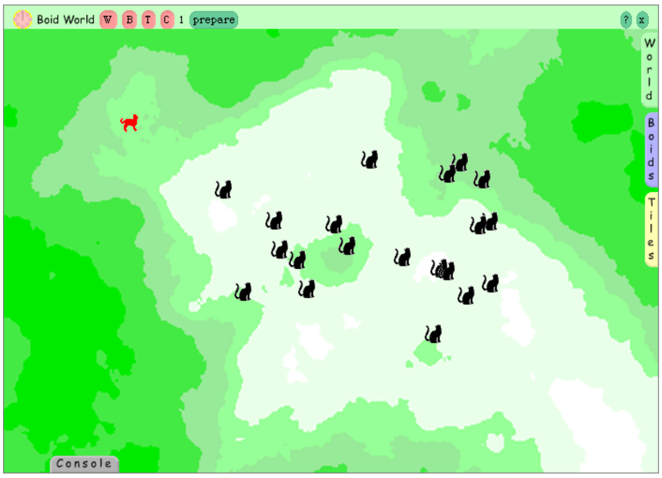


Figure 6-7: Fine DomWorld

Chapter 7

Testing

7.1 Unit Testing

There is a pre-installed unit testing framework, named SUnit, in Squeak. The scene of testing is seen in Figure 7-1. As its name tells, SUnit is one of xUnit testing framework series, which originate from Kent Beck's SUnit; it is, however, implemented on VisualWorks. He feels user interface-based tests brittle and prefers to test in programming language. A disadvantage of the way is obviously that a tester needs to know how to program on the language; nevertheless, the simplicity is still attractive. (Beck, 2005)

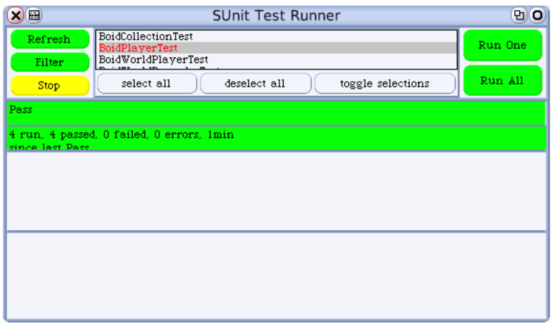


Figure 7-1: Scene Of Testing

Beck recommends that "developers write their own unit tests, one per class" (2005). There are, however, some types of classes unsuitable for the framework due to its feature; GUI and a concurrent system are two of them. A developer once asked him how to conduct unit testing about them but Beck answered that it is future work (personal observation of the author[1]). Unfortunately the framework developed in the dissertation has both aspects to some extents; accordingly, it is difficult to do unit testing for all classes. All things considered, only following classes are tested except for their GUI aspects on the testing framework because they are the

[1]at a seminar on TDD (Test-Driven Development) in Tokyo, April, 2001

kernels of kernel class.

- BoidWorldPlayerTest
- BoidPlayerTest
- BoidCollectionTest
- BoidWorldRecorderTest
- LineGraphMorphTest
- DataSeriesTest

An example of Test implementation is available in Appendix B.

7.2 System Evaluating

Most of core classes have been tested now, then the functions as a whole should be evaluated. The evaluation is actually executed at the same time as the first experiment of Chapter 9 because system test requires a model driven on the framework and the first experiment realises the most basic model. The confirmation is carried out along with the list in Section 3.4; the things which are confirmed are seen below.

7.2.1 Fusion Of Environments For Experiment And Development

Precisely this is verified by functions of the console tab. All Smalltalk expressions surely can be evaluated on the tab. For example, when an experimenter types '`world inspect.`' the inspector for `BoidWorldPlayer` instance is opened and it allows the user inspecting and modifying instance variables. If the user evaluates '`self browse.`' the class browser which displays the information of the simulator itself come up and it is even possible for the user to change the definition of the simulator on it. These agree with the requirement.

7.2.2 Composite Experiments

Both repeating one experiment and sequencing some experiments are possible by utilising `BoidWorldCompositeExperiment` class; however, the function has not been exploited very much because of the following two reasons. First most of experiments are regulated according to the result of the previous experiment so that it is a rare case to be able to decide full condition before finishing the previous. Secondly repeating one experiment can be implemented on an ordinal experiment without taking advantage of `BoidWorldCompositeExperiment`; besides, to be honest the subclass of an ordinal experiment class is more practical to handle the result than the common composite class. However, in spite of the above facts, the composite experiment must be useful for the future re-examination.

7.2.3 Easiness To Construct New Experiment

As seen in Chapter 9 many kinds of experiments have been executed on the framework. As long as the implementer becomes familiar with the system, it is even possible to create a new experiment in less than one hour. In addition, the tile scripting helps beginners to construct a simple experiment without knowledge of Smalltalk (see Appendix A) although it is not made use of in the dissertation. Accordingly the framework realises the required easiness with two means: a person of skill can construct new experiment in a short time and a novice can do it without special knowledge.

Part III

Experiment

Chapter 8

Introduction

8.1 Outline

The arrangement that more predominant individuals position themselves in more centre and less dominant on fringe is often observed in monkey troops (Seyfarth & Cheney, 2002). Hemelrijk demonstrated that the arrangement can emerge from their dominance interaction (2000*a*). The hypothesis, however, does not intend to explain which environmental pressure promotes the dominant nature of monkeys. Although it is generally said that the pressure may be food, predation, or both (Miller, 2002), there is no decisive evidence. The primate society is so complex that it is really difficult to extract one causal relationship from actual observed behaviours. A simulation is useful to analyse such complex phenomena [see section 2.2.3] because it allows for researchers to ignore redundant factors and to concentrate on important ones.

As explained earlier, the scene that a primate is caught by a predator has hardly been observed (Jolly, 1972, p. 70). For example, Miller wrote that she could not have observed any predation for about four year when she engaged in research at Hato Pinero (2002, p. 97). The fact, however, does not contradict the importance of predation in the society of primates. Granted that almost no one has directly seen the predation, the evidences that infant primates are eaten are often detected. In addition, the influence of a predator is supreme. There is a record that the mortality of vervet monkey at Amboseli, Kenya is originally about 50% however, once one leopard appeared on the site, it increased to 70% (Thierry et al., 2004, p. 90). A simulation can supplement the lack of observation. Using a simulation, researchers can confirm whether or not a hypothesis can connect observed initial state and observed result without direct observing the process.

This dissertation simulates primate behaviour with concentrating on dominance aspect of primate society and predation. If the less-dominants tend to suffer predation, it is likely that predation is one of environmental pressures causing primate social structure.

In order to examine the thesis some experiments are conducted in the following order. First of all it is checked how correspondent to Hemelrijk's DomWorld the implementation is in Section

9.1. Then the model is extended for monkeys to be able to react to a predator in Section 9.2. After that, a predator is introduced to the model in Section 9.3. Finally it is investigated how the predation affects dominance style of monkey troops in Section 9.4.

8.2 Terminology

8.2.1 Centrality

In DomWorld, it is made a point of where a monkey is located in its troop and the centrality is measured in the way illustrated in Figure 8-1.

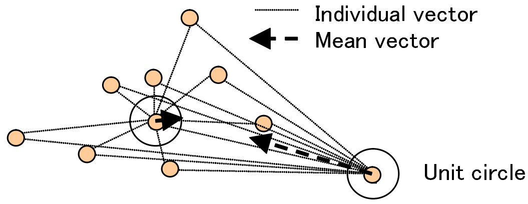


Figure 8-1: Centrality (Hemelrijk, 2000*b*)

Centrality is the sum of all unit vectors toward other agents and its size can be represent how centre the agent is in. As seen in Figure 8-1, large vector means the agent is in periphery; on the contrary small one means in centre (Hemelrijk, 2000*b*).

Note that 'centrality' sometimes means 'the ranking of the centrality' in the paper.

8.2.2 Coefficient of Variation (C.V.)

In order to compute how dispersed `Dom` its CV is often used. It is calculated as follows:

$$StandardDeviation = \sqrt{\frac{\sum(x-\overline{x})^2}{n-1}} \tag{8.1}$$

$$CV[\%] = \frac{StandardDeviation}{\overline{x}} \times 100 \tag{8.2}$$

Although the standard deviation itself can express the degree of dispersal it is affected by the original unit. CV is removed the effect by dividing standard deviation by mean value, so that it is suitable to compare with other CV values (Wikipedia, 2005*b*).

In Hemelrijk's original paper a raw value is used; however, in this paper it is multiplied 100 and handled as percentage.

8.3 Parameters

Since lots of experiments are carried out in the next section and the settings are different each other all settings are listed in Figure 8-2. Base parameters are illustrated on the top of the table and these values are used whenever values are not specified.

Section	Experiment	Repeat	MaxSteps	Species		number of	stepdom	initdom	searchangle	perspace	nearview	maxview	activate
						Base Parameter	1	8	90	2	20	50	random (1-10)
8.1 Confirmation of Being DomWorld	Fierce vs. Mild	1	10000	Fierce	Male	8	1	16	90	2	20	50	random (1-10)
					Female	8	0.8	8	90	2	20	50	random (1-10)
				Mild	Male	8	0.2	16	90	2	20	50	random (1-10)
					Female	8	0.1	8	90	2	20	50	random (1-10)
	Cohesive vs. Loose	1	10000	Cohesive	Male	8	1	20	180	2	20	50	random (1-10)
					Female	8	1	10	180	2	20	50	random (1-10)
				Loose (= Fierce)	Male	8	1	20	45	2	20	50	random (1-10)
					Female	8	1	10	45	2	20	50	random (1-10)
8.2 Modelling Vigilant Action	Position vs. Vigilance	1	2000	Monkey		20	1	8	90	2	20	50	random (1-10)
	Group Size vs. Vigilance	1	10000	Monkey		5,10,…35	1	8	90	2	20	50	random (1-10)
8.3 Effect of Dominance Interaction on Being Eaten	Attack Direction	5	40000	Monkey		20	1	8	90	2	20	50	random (1-10)
	Just Wandering	500	undecidable	Monkey		20	1	1,2,..20	90	0	20	50	random (1-10)
	Fight & Fixed Dom	500	undecidable	Monkey		20	0	1,2,..20	90	2	20	50	random (1-10)
	DomWorld with Loepard	500	undecidable	Monkey		20	1	8	90	2	20	50	random (1-10)
8.4 Effect of Asymmetric Dominance Interaction on Being Eaten	Despotic vs. Tolerance	500	undecidable	Despotic		5,10,15	1	8	90	2	20	50	random (1-10)
				Tolerant		15,10,5	1	8	90	0	20	50	random (1-10)
	Despotic vs. Egalitarian	500	undecidable	Despotic		5,10,15	1	8	90	2	20	50	random (1-10)
				Egalitarian		15,10,5	0.2	8	90	2	20	50	random (1-10)

Figure 8-2: Experiment Patameters

Chapter 9

Experiments

9.1 Confirmation of Being DomWorld

9.1.1 Introduction

The absolute reproduction of DomWorld is not the subject; however, DomWorld is important for the dissertation as a starting point. It is desirable that the tendencies of transition of a dominance value (known as `Dom`) seen in the model meets Hemelrijk's original DomWorld because it is the most essential feature in DomWorld.

Additionally this experiment is positioned to be the system test of BoidWorld framework. Functions required as a simulator such as creating new agents, setting up their properties with various values, introducing new experiments, collecting data, and displaying the result are all confirmed here and its results are summarised in Section 7.2.

9.1.2 Model

DomWorld itself is presented in Section 2.2.4, so that the concentration on this section is focused on the difference between the original DomWorld and the model in the dissertation.

Border of The World In the original world, the confronting borders are connected in spatial meaning. In the model used for the dissertation, although, borders are not dealt with in such special way. Borders are the ultimate limits of the world so that when agents go out of the world the simulation is stopped. In fact the world, which consists of 700 $\times$ 500 units, is so broader than the original, which includes 200 $\times$ 200 units, that exception has never been observed even when 100,000 time steps have elapsed.

Time Steps Because agents are activated at random intervals, a lapse of time is measured with the number of their activations in the original. 200 activations are counted as one step. In the present case, it is counted not by activations but by all time units. The intervals are chosen from uniform-distributed numbers from one to ten. Accordingly, when the number of agents is 20 the steps should be divided by 50[1] in order to roughly transform the time step in the dissertation into the original form.

First Position Since Hemelrijk has not stated the first positions of agents, they are located as following at the beginning of the world.

```
| radius |
radius := ((10 * 10 * Float pi * numOfMonkeys) / Float pi) sqrt asInteger.
initialGroupingArea := Circle new radius: radius; center: world center.
world shuffleBoidsInCircle: initialGroupingArea.
```

This means, each monkey has its territory whose area is same as a circle having a radius of ten. The area for the group is a circle whose area is sum of all individual's territories. All agents are randomly located in the group area.

Gender Finally, sexual distinction is introduced to experiments in this section for comparison with the original experiments but in other sections the division is never used. In order to avoid injecting unnecessary complexity sexual attraction examined in the original (Hemelrijk, 1999*a*) is not implemented.

9.1.3 Method

Though most parameters may affect a history of individual dominance Hemelrijk has written about only two factors: the combination between `StepDom` and `InitDom` representing fierce/mild species (1999*a*) and `SearchAngle` standing for cohesive/loose species (1999*b*). In the section the inclination of these two aspects are examined to be same as the original.

Fierce vs. Mild The parameters used for the two species are listed in Table 9.1; parameters which are not itemised in the table are set for the base value, which are shown in Figure 8-2. In both sexes of fierce species has larger `StepDom` than that of the same gender of mild species. This means an aggressive interaction results in more immense change of `Doms` for both sexes in the fierce species.

Procedures for both species are certainly the same. Each gender consists of eight individuals. The world is driven for 10,000 steps and `Doms` of all monkeys are recorded in every step.

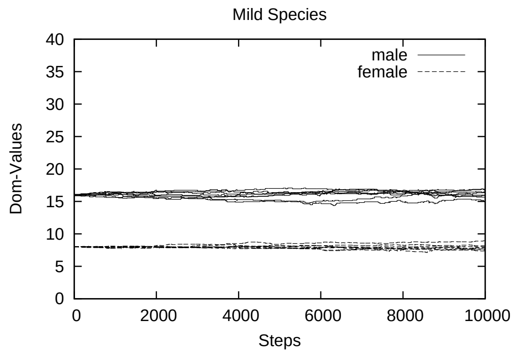
Cohesive vs. Loose The particular settings are illustrated in Table 9.2. Other conditions are the same as the previous experiment. All `Doms` of eight males and eight females are observed for 10,000 steps.

	VirtualFemale	VirtualMale
StepDom of		
Fierce species	0.8	1.0
Mild species	0.1	0.2
InitDom	8.0	16.0
SearchAngle	90	90

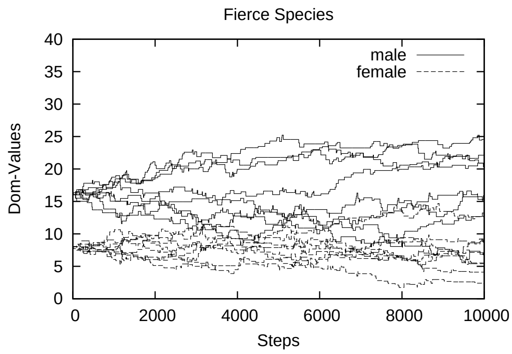
Table 9.1: Parameter and initial values for Fierce vs. Mild

	VirtualFemale	VirtualMale
StepDom	1.0	1.0
InitDom	10.0	20.0
SearchAngle of		
Coherence species	180	180
Loose species	45	45

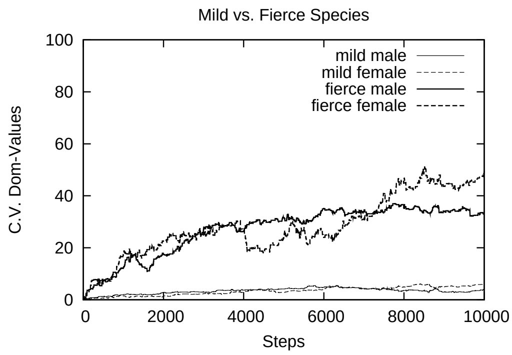
Table 9.2: Parameter and initial values for Cohesive vs. Loose



(a) Mild Species

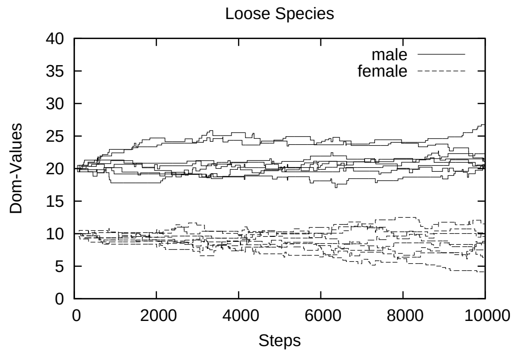


(b) Fierce Species

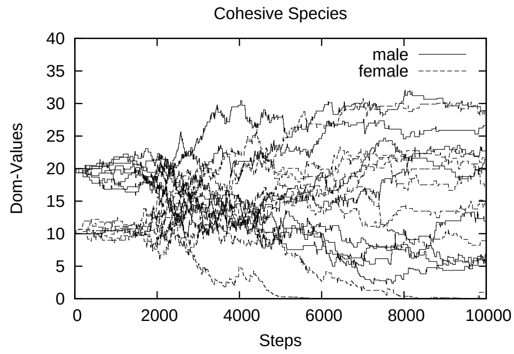


(c) C.V for Both

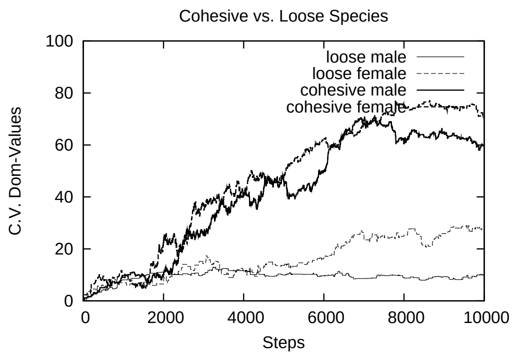
Figure 9-1: History of Dom for Mile/Fierce Species



(a) Loose Species



(b) Cohesive Species



(c) C.V. for Both

Figure 9-2: History of Dom for Loose/Cohesive Species

9.1.4 Result

Histories of `Dom` for each species are exhibited in Figure 9-1 and 9-2. The all tendencies of them are fully agreeable with Hemelrijk's results (1999*a*, 1999*b*).

Roughly speaking, fierce is to mild what cohesive is to loose. Both fierce and cohesive species promote overlapping dom values between male and female faster than their respective opponents. Additionally, it is likely some females overcome males as a result of the promotion. The difference of diversion of `Dom` can be seen in the C.V. (Figure 9-1(c), 9-2(c)). The reason for the furtherance is, however, different from each paring. Concerning comparison of fierce with mild species the point is in significance of one aggressive interaction while in case of coherence the frequency of violent behaviours should be paid attention with.

As a conclusion, the model can be regarded as a pseudo-DomWorld.

9.2 Modelling Vigilant Action

9.2.1 Introduction

Though it is possibly assured that the compatible world with Hemelrijk's DomWorld has been constructed in the previous section, there is one more thing that has to be done before introducing a predator in the world. While a predator may keep seeking for prey, namely monkeys in the case, monkeys can not care about predators at all times because they have a lot of other things to do although a predator is certainly one of their largest concerns. Accordingly, it is necessary to decide when monkeys mind a predator.

Apart from a point of contact with a predator, vigilant action is still significant because the time spent for feeding is in inverse proportion to the frequency of vigilant action (Miller, 2002, ch.12). In addition, vigilant action is aroused not by existence of predators but by prospects of the existence (Miller, 2002, ch.14). Even if the only predator living in a certain food patch has died monkeys may keep more vigilant on condition that they do not know the death than other patch where they realise a predator seldom occur.

In addition, although the following is out of the scope of the dissertation alarm calling is also important as a fork where other anti-predator behaviours stated in Section 2.1.4 are chosen and invoked.

9.2.2 Model

The model must be grounded on Hemelrijk's DomWorld Model (Hemelrijk, 1999*b*), which have already been implemented in Section 9.1. Utilising it, the devised model for the dissertation is seen in Figure 9-3.

From the viewpoint of action of monkeys, vigilant action (i.e. `LEOPARD <= MAXVIEW`) is in the same level as cohesive action (i.e. `OTHER <= MAXVIEW`) in the model. The author assumed

[1] namely $OriginalActivationUnit \div (TheNumberOfMonkeys \div AverageActivationInterval) = 200 \div (20 \div 5) = 50$

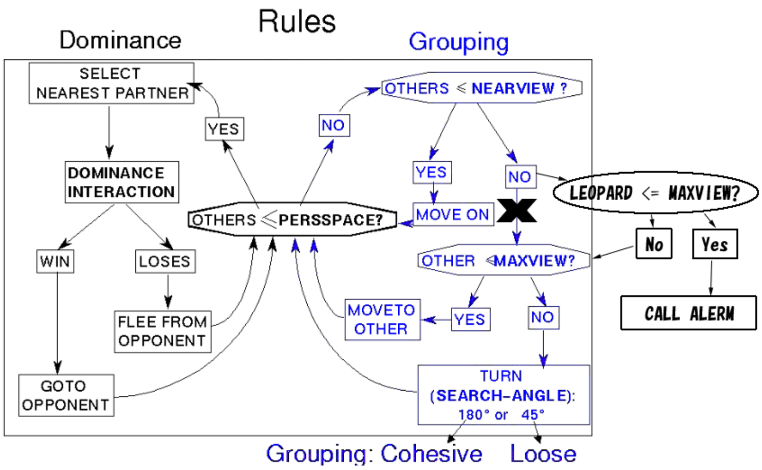


Figure 9-3: DomWorld Built in Vigilant Action (based on Hemelrijk (1999*b*))

the both are the same searching action presumably resulting from anxiety. It feels natural assumption owing to the fact that monkeys must react if they detect a predator when they are looking for their neighbours at the fringe of the group. Their priorities are, however, different because the existence of a predator is fatal to prey, while that of neighbours can give them just relief. Accordingly, the check of the existence of a predator precedes that of neighbours in the model.

The above model is adopted hereafter in the dissertation so that the validity of the model is tested first of all in this section.

9.2.3 Method

There are two well-known characteristics of vigilant actions from statistical point of view. Firstly, individuals in a large group are less vigilant than in a small group because they can rely on their neighbours for precaution to some extent (Miller, 2002, ch.12) and probably because the existence of neighbours relieve them from being eaten on account of the effect of dilution. The second characteristics is that monkeys in the more central are less vigilant than in periphery (Miller, 2002, ch.16). This is because individuals in fringe are expected to be targeted by predators more than in centre especially in case of those of terrestrial.

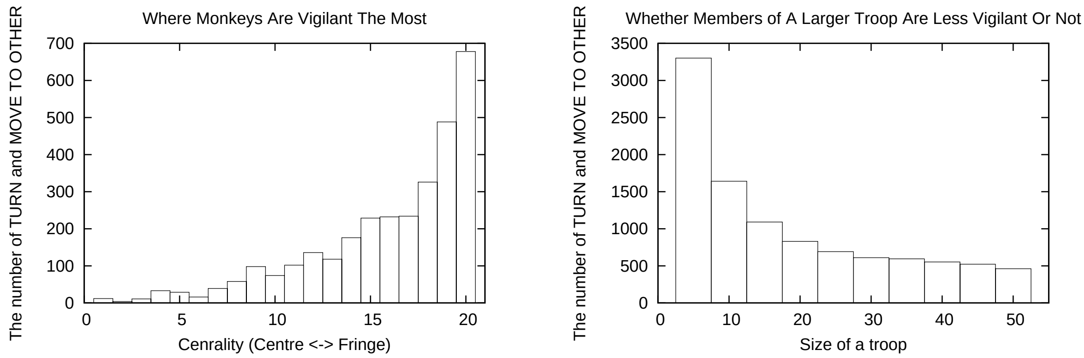
The two features, cohesion and centrality, related above respectively are generally regarded as the reason why animals make a group (Hamilton, 1971). In addition to the fact, they are directly related to the vigilant action, so that the model adopted for the dissertation must satisfy at least these two traits.

As stated in Section 9.2.2 the check whether the others can be seen within the `MAXVIEW` distance or not in plain DomWorld happens in the same condition as the vigilant action in the extended DomWorld. In other words, to investigate the feature of the cohesive action means to look into the vigilant action. Based on the idea, the following two experiments are executed in order to corroborate the extended model.

Where Monkeys Are Vigilant The Most The base parameter setting concerning monkeys' behaviour (that is, StepDom=1, InitDom=8, SearchAngle=90, PerSpace=2, NearView=20, MaxView=50) is used for the experiment. First, 20 monkeys are located at their first position. Then the world is driven for 2,000 steps. Every `TURN` and `MOVE TO OTHER` action, which represents a vigilant action in the case, is recorded together with the centrality of the turner. Finally the number of vigilant actions per centrality is counted.

Whether Members of a Larger Troop Are Less Vigilant or Not Individual settings are the same as the previous experiment. The size of the monkey troop is increased from five to 50 by five and all `TURN` and `MOVE TO OTHER` actions in 10,000 steps are summed up respectively. The sums are divided by the number of monkeys in the end.

9.2.4 Result



(a) Centrality

(b) The Size of Troop

Figure 9-4: Characteristics Of Vigilant Action

As seen in Figure 9-4, the tendency completely agree with the expectations; that is, monkeys in fringe is more vigilant than in centre (Figure 9-4(a)) and those in larger troops are less vigilant than in smaller troops (Figure 9-4(b)). The fact backs up the model expressed in Figure 9-3.

9.3 Effect of Dominance Interaction on Being Eaten

9.3.1 Introduction

Now monkeys can move around in DomWorld with occasional vigilant actions so that it must be a good place to introduce a predator onto the model and to investigate the influence. Obviously the series of experiments included in the section are substantial for the thesis.

9.3.2 Model

The main point is not to reproduce the scene of real predation but to probe the effect of predation on a monkey troop statistically; therefore, the beginning of both models of monkey and leopard should be as simple as possible.

Leopard's Preying As described in Section 2.1.5, the style that a leopard preys highly depends on its surroundings. Some of those in savannah hunt at night (Busse, 1980), others in rain forest ambush in the daytime (Zuberbühler & Jenny, 2002).

Hemelrijk's model is adopted as a starting point and the model addresses a macaque (genus *Macaca*) society. Because most macaque species are diurnal, the time when dominance interactions are breaking out in the model is the daytime. As a conclusion, the hunting must be occurred in daylight and it leads that the leopard hunting strategy is *ambushing*.

Consequently some trees are introduced on the world in addition to a predator. As well as they act as lurking places for a predator at the beginning of an experiment, after the predator finds a prey they turn their roles to refuges for monkeys.

Algorithm For Leopard's Hunting The way that a leopard enters in the world is somewhat tricky; accordingly the procedure is explained in a little detail below. Note that the procedure is common to downward experiments. At first leopards exist under all trees, which are represented by six circles in Figure 9-7. Though all of them are ambushing passing monkeys only one leopard can be activated and changed its state to pursuing. When a monkey comes closer to a leopard than a certain distance the leopard starts hunting and at the same time other leopards are prohibited from hunting and forced to keep waiting until the end of the session. This allows monkeys to take refuge in trees where other leopards were in. The reason why such awkward way is adopted is because it cannot be anticipated in which direction the troop moves as a whole. Therefore it is necessary for the system to be able to deal with the movement in all directions.

Once a leopard shoots out of a tree, the algorithm to pursuit is quite simple. It directly approaches the nearest monkey until catching it. Leopards are activated twice frequency of monkeys' activation (i.e. leopards can run twice faster than monkeys) so that it is almost impossible for them to succeeded fleeing without any victims in the dissertation's case.

Monkeys' Anti-predator behaviour Although some of anti-predator behaviours are introduced in Section 2.1.4, it is natural that the first behaviour which a monkey detecting a predator executes is alarm calling. The problem is next behaviour.

As for the thesis, fleeing is chosen as the second action because it looks the most appropriate as well as other behaviours which are listed in Section 2.1.4, namely protecting others, freezing and mobbing, seem not to be suitable for the starting point. Protecting others must require more complicated model for internal state of a monkey (that is, when and whom it protects and why) than DomWorld; besides, the behaviour can be observed only in the limited species (e.g. Busse, 1980). Then, freezing is also seen in limited situations. Some of them are depends on the monkey's mingling with its surroundings for its success and often executed in a tree (Miller, 2002, p. 44). Others are performed when the predator is less agile than the monkey (e.g. snakes (Nishida & Uehara, 1999, ch. 7)). Unfortunately both cases are not the case of the dissertation; a leopard, which is more rapid than monkeys, preys when monkeys are interacting each other on the ground. Lastly mobbing is stated. Although the behaviour is quite interesting for the author and must fit for DomWorld it is irrelevant as an anti-leopard behaviour because a leopard is an overwhelmingly good hunter for monkeys (Busse, 1980). Accordingly, mobbing may not effective toward leopard's hunting.

On the contrary, fleeing is free from all above disadvantages and quite suitable for DomWorld in the point that it is purely spatial problem, as well as it is the most common anti-predator behaviour.

Algorithm For Monkey's Fleeing Shortly the way for a monkey to choose a refuge is illustrated following. At first they look for a tree which they can reach before caught by a predator. If there is not any proper tree they run away in the opposite direction to the predator.

On condition that a leopard can run twice faster than monkeys and monkeys run straight, the area where monkeys can arrive at without being caught by a predator is shown in Figure 9-5. If any refuge can be included in the area monkeys go for the nearest, otherwise run away from a predator.

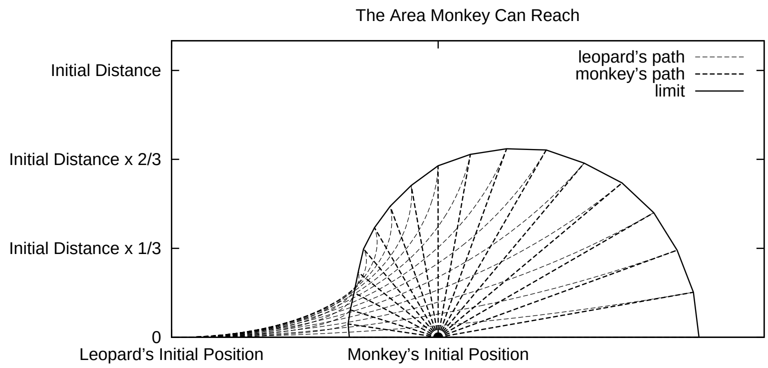


Figure 9-5: Reachable Area before Capture

When the angle between a predator and a refuge seen from a monkey is coined a_m[rad] the approximation [2] of reachable distance corresponding to the a_m can be got as below.

$$ReachableDistance = \frac{InitialDistance}{3} \times \cos(a_m) + \frac{2}{3} \times InitialDistance \tag{9.1}$$

If there is a tree within the reachable distance from a monkey, it can escape to the tree safely. The agreement between the approximation and the actual value is enough as demonstrated in Figure 9-6.

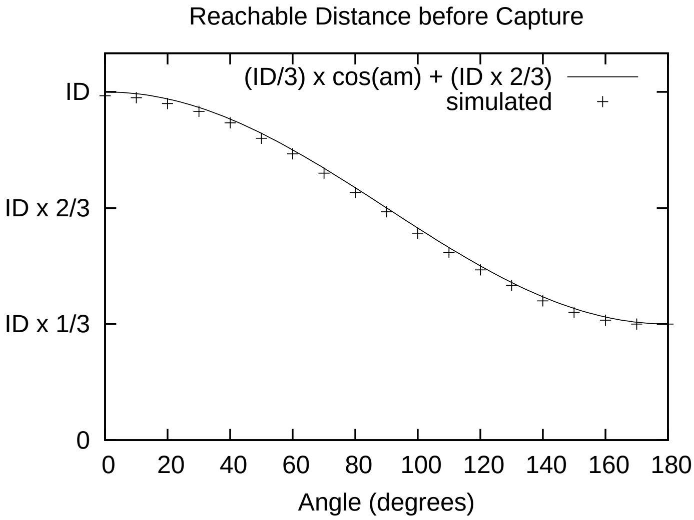


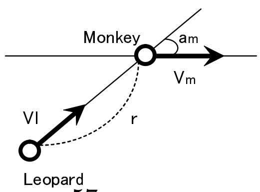
Figure 9-6: Comparison Measured Values With Calculated. The dots are actually measured distance on the framework and the line is obtained from the approximation equation.

9.3.3 Method

The Direction of Dominance Interaction Before investigating the relationship between dominance interaction and predation, it should be looked into what kind of role the dominance interaction acts in a monkey troop at first. Although Hemelrijk has examined that dominance interactions result in the hierarchical structure of troops (2001)is the characteristics of the in-

[2] Although it is rejected in order to avoid introducing unnecessary complication and making the process slow in the case, the exact value can be acquired by solving the kinetic equation:

$$\begin{cases} \dfrac{dr}{dt} = V_m \cos(a_m) - V_l \\ \dfrac{da_m}{dt} = -\dfrac{V_m \sin(a_m)}{r} \end{cases}$$



teraction itself in DomWorld have not been published. In the first experiment of the section, it is analysed where and to which direction the aggression happens the most in order for consideration for the results of experiments. Precisely, the dominance interactions of 20 monkeys set up with base parameters are kept being recorded for 40,000 steps in basic DomWorld, where there is not any predator, and finally all its position and direction is summed up.

Relationship Between DomValue and Centrality In addition to the above another inspection of DomWorld is carried out. Although one snapshot which illustrates predominant individuals is in centre of a troop and subordinates are in fringe (Hemelrijk, 2001) the snapshot cannot tell that the spatial structure is kept at most of times. In the experiment both DomValue and centrality of all monkeys are recorded for 5000 steps in order to compare DomValue with centrality directly.

Without Dominance Interaction In the world for this experiment all monkeys are completely pacifist. Though they have their own `Dom` the values will not be changed because monkeys just wander as they like and do never aggress to others. Practically speaking, their `PerSpace` is set to zero, which result in avoiding any dominance interaction (see Figure 9-3). Without dominance rules, the grouping rule is still valid so that they can form a troop. The troop is stocked with in the forest where a predator is ambushing (see Figure 9-7).

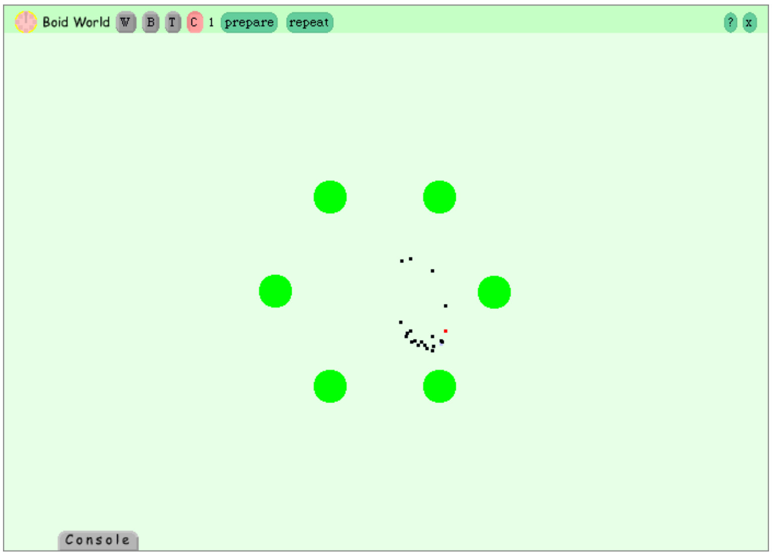


Figure 9-7: The Scene of A Experiment

At the beginning of the experiment 20 monkeys whose `Doms` are set from 1 to 20 respectively are located in their initial position and six trees are placed surrounding the troop. Then the world start to be driven until a leopard catches a victim.

The experiment is repeated 100 times with recording data about victims, such as their `Dom` and centrality. The result of the experiment is just used as criterion for other experiments in

	No Aggression	Fixed Dom	Normal DomWorld
StepDom	1 (ignored)	0	1
InitDom	1,2,...,20 (fixed)	1,2,...,20 (fixed)	8 (variable)
PerSpace	0	2	2

Table 9.3: Parameters

the section.

With Dominance Interaction Which Does Not Change Dom While dominance interaction itself is deterred in the previous experiment, the influence of dominance interaction is restricted this time. In brief `StepDom` is set zero instead of nonzero `PerSpace`. Zero `StepDom` eliminates the side effect from dominance interaction which is given by the equation in Section 2.2.4. In other words the troop has static hierarchical structure. In fact the hierarchical structures of most macaques are not so flexible as represented in Hemelrijk's model; accordingly, it is likely the model addressed in this experiment stands for actual monkey troops better than Hemelrijk's one. The comparison of the result of this experiment with that of next experiment (ordinary DomWorld) may provide some interesting knowledge. Any other things such as the procedure and collected data are absolutely similar to the previous experiment.

With Dominance Interaction This experiment is clearly the heart of the dissertation. Monkeys' parameters are all set for regular values and the influence of a predator on the troop is scrutinised. Comparing with above two experiments, `Dom` can be varied with the result of dominance interaction; accordingly, the hierarchical structure of the troop is dynamic. The process is same as the experiments mentioned above.

Distinctive parameters of these three experiments are summarised in Table 9.3.

9.3.4 Result

The characteristics of dominance interaction in DomWorld can be seen in Figure 9-8. The most distinguished feature is the position where dominance interactions are carried out the most. As observed in Figure 9-8, dominance interactions are apt to be acted in the central, where the value of centrality is low, and the edge, high centrality value, on the contrary the numbers of them are relatively small at intermediate position.

The most remarkable point is, however, another. The result demonstrates that dominance interaction encourages dominant individuals to be located in more central. Unfortunately the fact is hard to tell just seeing Figure 9-8, so that data is processed using the following equation.

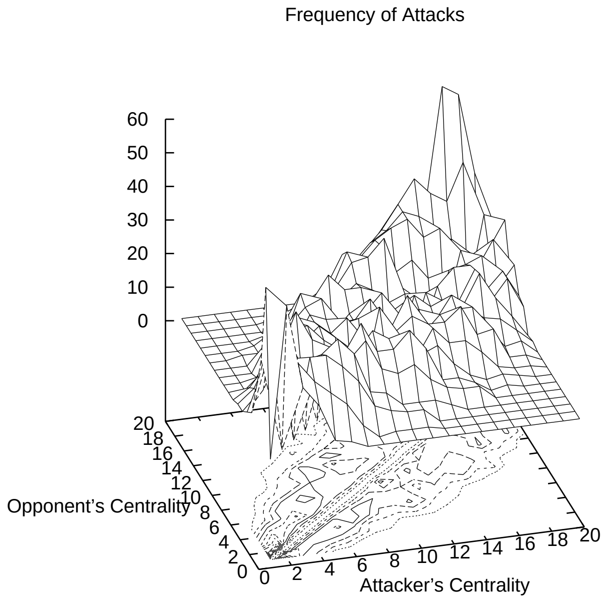


Figure 9-8: Attack Direction

$$Direction = InwardAttack - OutwardAttack \tag{9.2}$$

$$InwardAttack = \sum_{c_d=c_a+1}^{n} \sum_{c_a=1}^{n-1} N(c_a, c_b) \tag{9.3}$$

$$OutwardAttack = \sum_{c_d=1}^{c_a-1} \sum_{c_a=2}^{n} N(c_a, c_b) \tag{9.4}$$

$Direction$: if positive, most attacks are done inward; if negative, outward.
$N(c_a, c_b)$: the number of attacks
c_a: attacker's centrality
c_d: defender's centrality
n: the number of monkeys

In brief, the equation compares the number of aggressions in the central direction with that of in the outer. Accordingly, the result of positive value means that the number of all inward attacks in 40,000 steps is more than that of outward ones.

The consequences of the calculation for five trials are offered in Table 9.4. The table tells that about 60% of attacks are done in central direction. In other wards, taking it into consideration

Trial (40,000 steps)	1st	2nd	3rd	4th	5th	The Sum
$InwardAttack$	2253	2224	2133	2135	2110	10855
$OutwardAttack$	1669	1529	1523	1583	1562	7866
$Direction$	584	695	610	552	548	2989

Table 9.4: Difference Inward Attacks and Outward Ones

that a dominant monkey makes a pre-emptive attack against a subordinate, the dominance interaction is executed not in order for dominants to prevent subordinates coming into but to thrust dominants' way in through the lower-rankings in the direction of centre. Consequently, the dominance interaction may work as an assistant force to keep a group coherent and make a dominant individual be in more centre.

Additionally the relationship between centrality and dominance value is inspected. The Figure 9-9(a) demonstrates the number of each combination of centrality and dominance value of a monkey in 5,000 steps. The Figure 9-9(b) represents the same and dots point the places where the number is the largest, namely the tone is the darkest, per dominance value (x-axis) in order to make explicit the correlation between centrality and dominance value. The line is obtained by the method of least-squares and shows that there is negative correlation between them. As a consequence there is a tendency that the more dominant monkey locates itself in more central position.

The results of the other three experiments with a predator are given in Figure 9-10. Regardless of feature of dominance interaction, monkeys at the edge of their troop are most likely to fall a victim as expected (see Figure 9-10(a), 9-10(c), and 9-10(e)). In every cases, more than 70 percent of victims are those who are in the top three most outer positions when preyed.

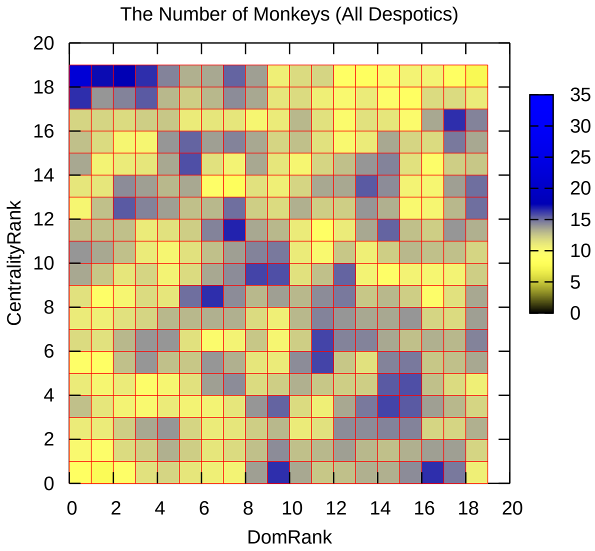
It can be read that dominance interaction biases the dominance values of preys based on the fact that the distribution of victims in Figure 9-10(b), where any dominant interaction does not happen, is comparatively flat while other two distribution is biased. On the contrary, Figure 9-10(d) and Figure 9-10(f) are quite similar to each other. Accordingly it may not be very important whether the `Doms` are fixed or variable. The fact is revisited in Chapter 10.

9.4 Effect of Asymmetric Dominance Interaction on Being Eaten

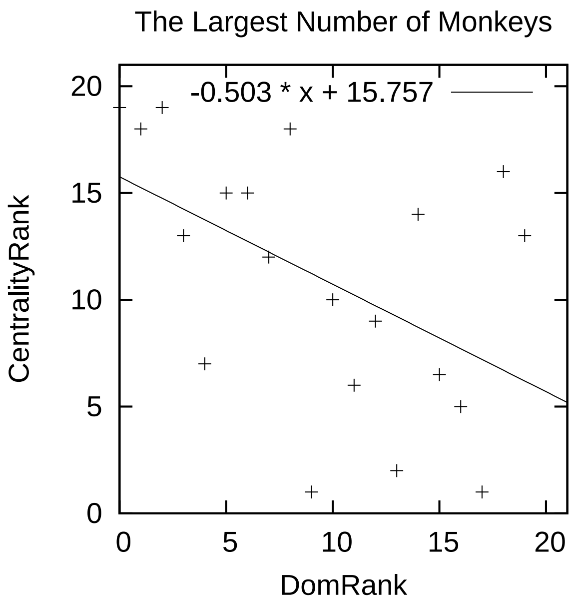
9.4.1 Introduction

There are various Macaque social styles in the present world; they, however, are not independent of each other. Thierry classified the styles according to behavioural characters and graded the classes into four groups in relation to interindividual tolerance; besides, he mapped the grades onto phylogenetic tree of macaques (see Figure 9-11) (Thierry et al., 2004, ch. 12).

As seen in the figure, species which are near each other on the phylogenetic tree tend to

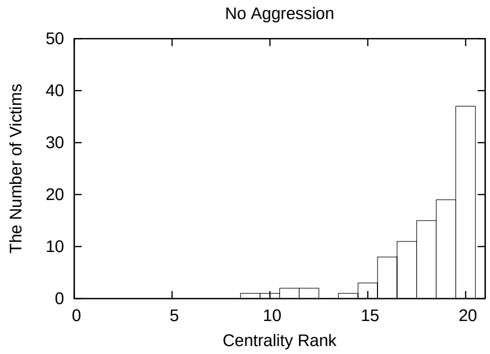


(a)

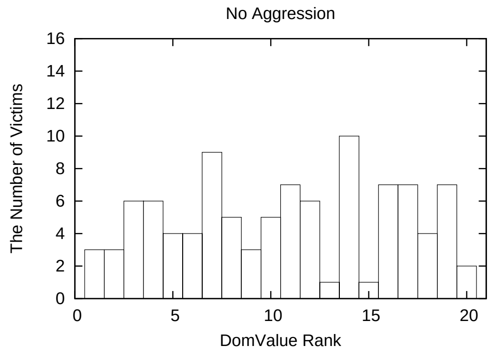


(b)

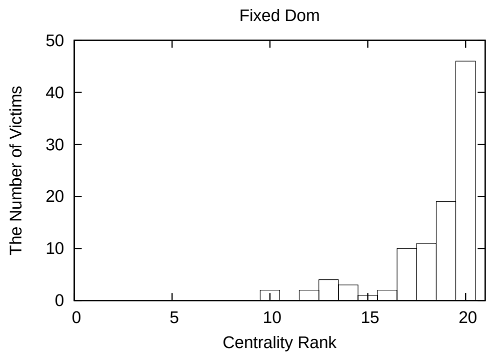
Figure 9-9: Correlation Between Centrality And Dominance Value



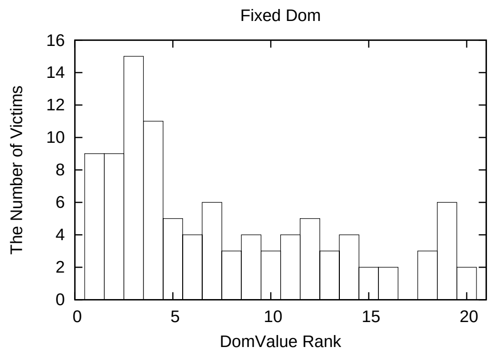
(a) Victim's Centrality Rank for No Aggression



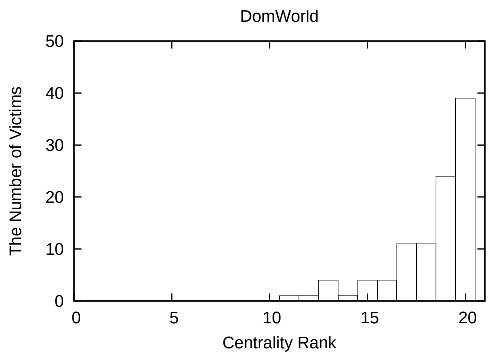
(b) Victim's DomValue Rank for No Aggression



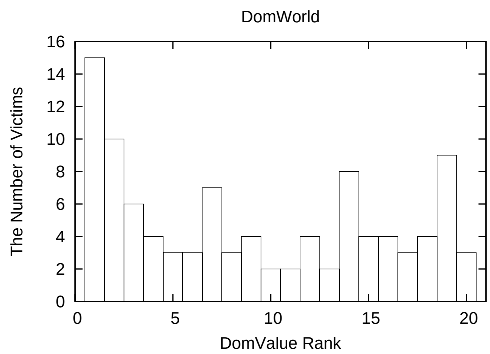
(c) Victim's Centrality Rank for Fixed Dom



(d) Victim's DomValue Rank for Fixed Dom



(e) Victim's Centrality for Normal DomWorld



(f) Victim's DomValue Rank for Normal DomWorld

Figure 9-10: Victims Distribution On Some Conditions

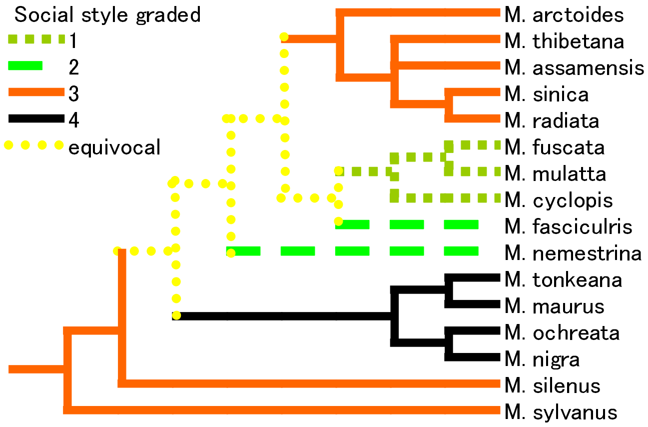


Figure 9-11: The Distribution Of Social Styles On A 4-grade Scale In Mapped Onto The Phylogenetic Tree Of Macaques (Thierry et al., 2004, p.284). Interindividual tolerance increases from one to four.

belong in the same grade of social style. This probably means that the styles have gradually changed owing to certain selective pressure along with biological evolution. The issue of the section is whether and how predation plays a role as the selective pressure at the transitive points.

9.4.2 Method

Although one of popular methods to explore such alternation of generations is actually to repeat revising the constitution of a generation according to their fitness, a more fundamental way is adopted as a preliminary this time. Precisely, the characteristics of mixed troops with static composition are investigated. If either natured individual have more tendency to fall prey than another predation possibly plays some role in the evolution of primate social style.

As concluded so far, the position of a monkey has a large effect on being prey as well as the dominance value biases the position in DomWorld. Providing the initial dominance value (`InitDom`) is fixed there are two variables which affect history of dominance value, namely the size of personal space (`PerSpace`) and the intensity of aggression (`StepDom`) (refer Section 2.2.4). Clearly, the former affects the frequency of dominance interaction and the latter influences the result of one interaction. In this section it is studied how the variations of these two variables have an impact on being eaten respectively.

Despotic vs. Egalitarian (Variation of StepDom) The procedure of the experiments is completely similar to the last three experiments in Section 9.3. Only a difference is the composition of the troop. This time, there are two species: one significantly receives the result of dominance interaction, and another regards it as a matter of not much interest. Whilst the former species is called 'Despotic', the latter is named 'Egalitarian'. Specifically egalitarian is

		Despotic	Egalitarian	Tolerant
vs. Egalitarian	The Number	5/10/15	15/10/5	-
	StepDom	1.0	0.2	-
	PerSpace	2.0	2.0	-
vs. Tolerant	The Number	5/10/15	-	15/10/5
	StepDom	1.0	-	1.0
	PerSpace	2.0	-	0.0

Table 9.5: Parameters

Despotic:Egalitarian	5:15	10:10	15:5
Despotic	142 (28.1%)	271 (53.7%)	406 (80.4%)
Egalitarian	363 (71.9%)	234 (46.3%)	99 (19.6%)
Statistically Significance	0.0599	0.0545	0.0025

Table 9.6: The Proportion Of Despotics To Egalitarians in Victims

realised by setting its `StepDom` to much lower value than that of despotic. Actual values of parameters are listed in Table 9.5. The proportion of despotics to egalitarian in whole troop varies 5:15, 10:10, and 15:5.

Despotic vs. Tolerant (Variation of PerSpace) In the experiment, some of monkeys act dominance interactions in the same way as usual DomWorld and others just respond to challenges but never attack first. The result of aggression equally affects both species as directed the equation 2.2 and 2.3. The latter species is called 'Tolerant' in this section. Because monkeys in DomWorld possibly attack the opponent when their range of personal space is invaded, tolerance is achieved by making their personal space zero. The proportion of tolerant agents is varied in the same way as the previous.

The characteristic parameters of each species are listed in Table 9.5.

9.4.3 Result

Despotic vs. Egalitarian

The proportion of despotics to egalitarians in the number of victims are shown in Figure 9-12 and Table 9.6. According to the statistically significances seen in the table, only the case of 15:5 is accepted and other two are rejected supposing the significance lebel is 0.05; however, the two can be said to be on the borderline and taking it into consideration that all combinations are biased on the same side, it may be said that despotic nature makes the monkey more dangerous to be eaten than egalitarian in a heterogeneous troop in the author's opinion. The detail of the victims is shown in Figure 9-13.

The distributions of the total number of victims on both centrality and dominance value seen in Figure 9-13 are similar to the case of a homogeneous troop (refer Figure 9-10(e) and 9-10(f)).

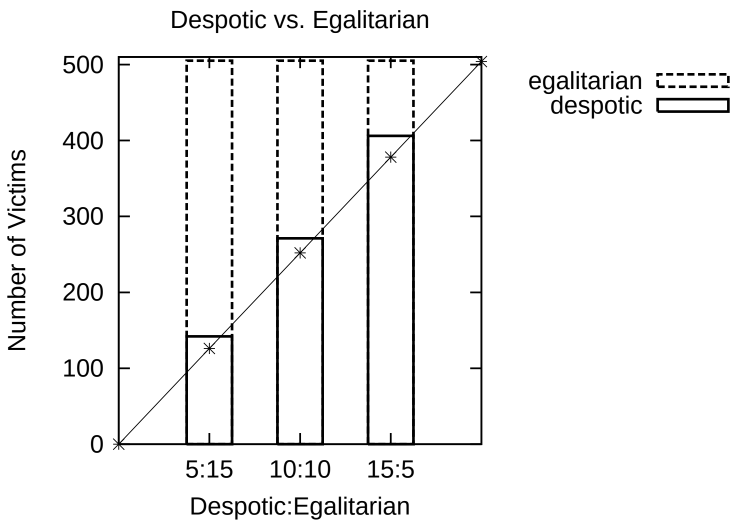
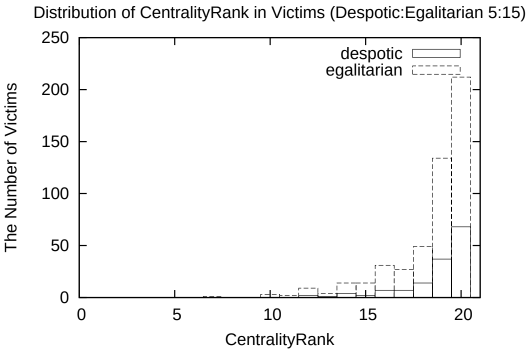


Figure 9-12: The Proportion Of Despotics To Egalitarians in Victims

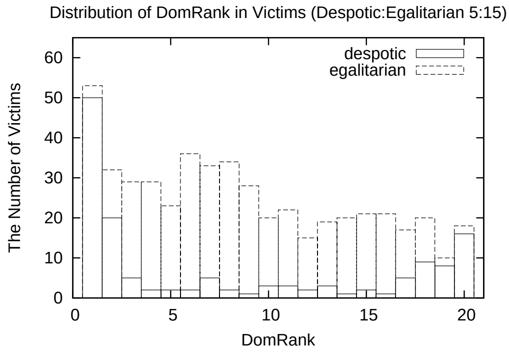
There may not be seen notable characteristics in the right graphs, concerning the centrality. The proportion of each species is almost equal to that of whole victims at all centralities. On the contrary obvious bias can be observed in the graphs about the dominance value. Most of both lower and higher-ranked victims are despotic, while victims having mean dominance value are mostly occupied by egalitarian. Incidentally, taking the bias into consideration the regularity of the centrality graph is rather odd because there is a correlation between dominance value and centrality as seen in Figure 9-9; that is, predominant monkeys tend to be in centre of their troop. Figure 9-14 can help to understand the reason of the oddity. The figure illustrates dominance values and centralities for not only victims but also all other despotics when they are attacked by a leopard. Precisely they are the combinations of dominance value and centrality of all monkeys measured just before statuses of monkeys are changed from normal to refuging. Although only the graph about the troop composed of ten despotics and ten egalitarians is provided the same tendency as stated above can be seen in the cases of other compositions, namely 5:15 and 15:5.

In Figure 9-14(a), values on z-axis mean the total number of despotics in 500 trials whose ranking of `Dom` and centrality are directed x-axis and y-axis respectively. The graph tells that there is a positive correlation between the ranking of centrality and the number of despotic victims in the region of lower ranking of `Dom` while it is negative in higher. These opposite tendencies offset each other; as a result, the graph from the viewpoint of centrality looks flat (refer Figure 9-14(c)).

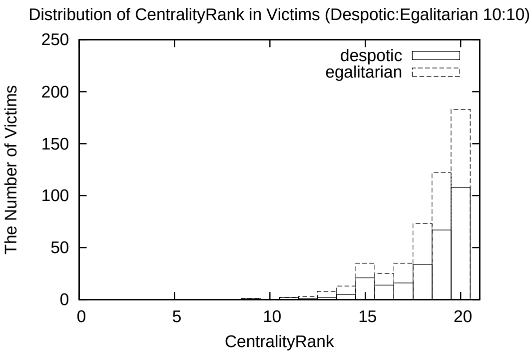
While Figure 9-14 demonstrates the spatial distribution of `Dom`, Figure 9-15 offers temporal one. Although the average number of interactions of each species may be equal because their decisions whether they attack or not are based on the same logic the influences of the result of the interaction on egalitarians' internal states is less than those of despotics. As a result



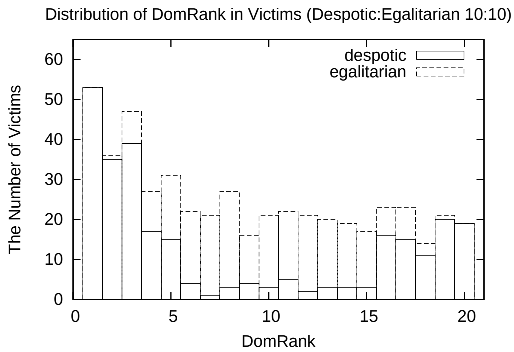
(a) Victim's Centrality Rank for 5/15



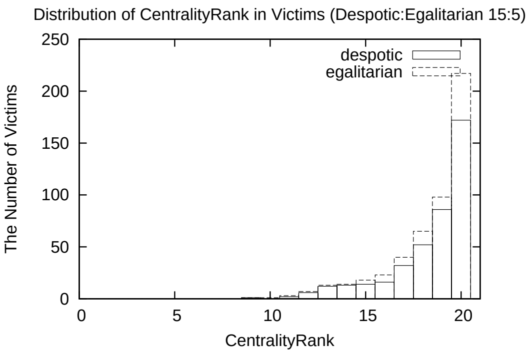
(b) Victim's DomValue Rank for 5/15



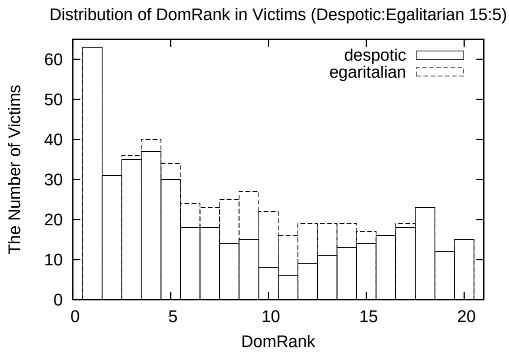
(c) Victim's Centrality Rank for 10/10



(d) Victim's DomValue Rank for 10/10

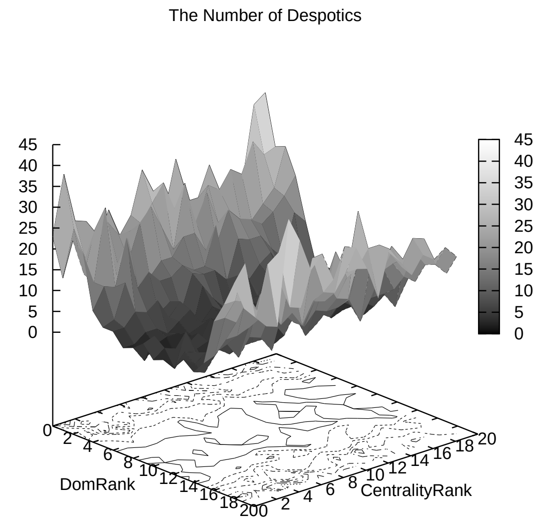


(e) Victim's Centrality for 15/5

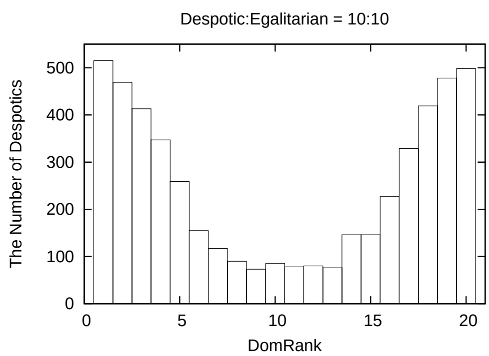


(f) Victim's DomValue Rank for 15/5

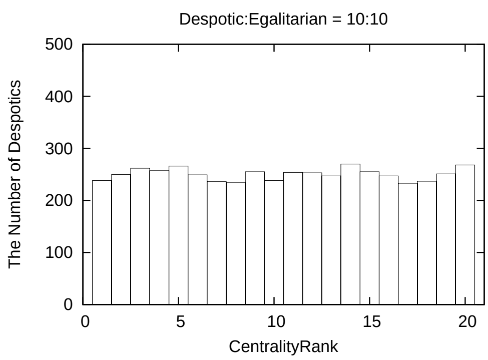
Figure 9-13: The Detail Of Victims (Despotic vs. Egalitarian)



(a) The Number Per Combination Between Dom And Centrality



(b) The Number Per Dom



(c) The Number Per Centrality

Figure 9-14: The Sum Of Despotics' Status When Attacked By A Leopard (Troop Composition: 10 despotics and 10 egalitarians)

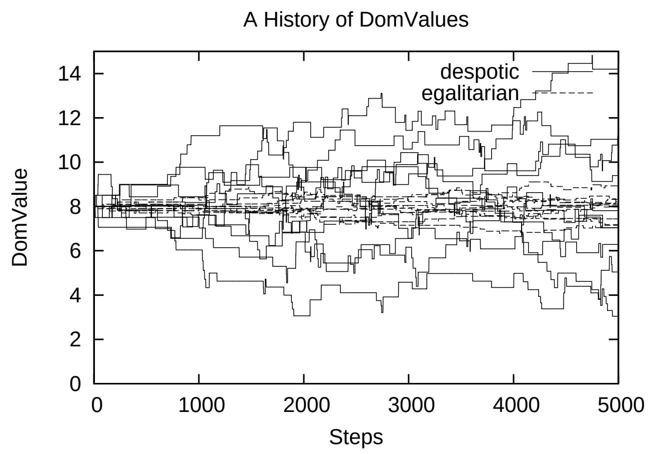


Figure 9-15: Typical Progress of DomValue (Troop Composition: 10 despotics and 10 egalitarians)

an egalitarian's `Dom` has tendency to remain initial value while despotic's largely goes up and down.

Despotic vs. Tolerant

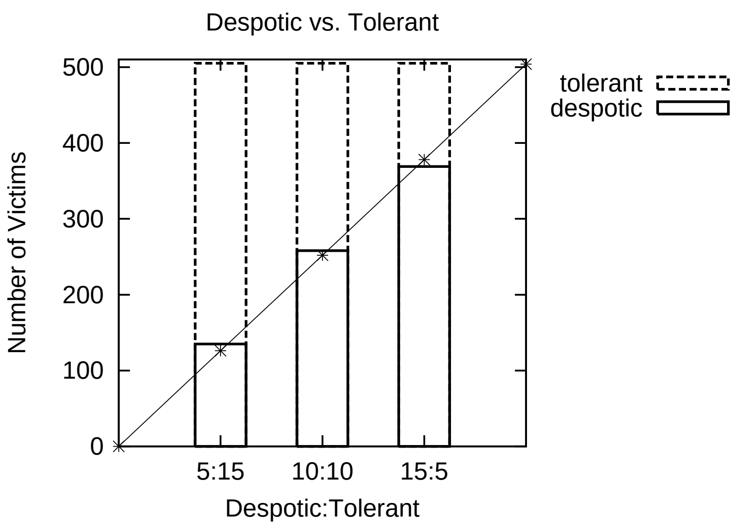


Figure 9-16: The Proportion of Despotics to Telerants in Victims

The results in the case of tolerant are shown in Figure 9-16 and Table 9.7. Disagreeing with the expectation, the proportion of despotics to tolerants in the number of victims is completely correspondent with the proportion of them in a troop. Consequently, it should be concluded

Despotic:Tolerant	5:15	10:10	15:5
Despotic	135 (26.7%)	258 (51.1%)	369 (73.1%)
Tolerant	370 (73.3%)	247 (48.9%)	136 (26.9%)
Statistically Significance	0.1976	0.3282	0.1707

Table 9.7: The Proportion Of Despotics To Tolerants in Victims

for the moment that predation does not affect the evolution of the nature of monkey troops concerning despotic or tolerant as long as standing on the model. To confirm the conclusion and to examine what kind of difference between the case of egalitarian and tolerant there is, other results are mentioned below.

Details of victims on each condition are listed in Figure 9-17. Graphs about centrality (upper ones) are just ordinal. The tendency is same as above (refer Figure 9-10 and 9-17). On the other hand, concerning `Dom` (Figure 9-17(b), 9-17(d), and 9-17(f)), it can be grasped that the existence of tolerants disturbs the ordinal distribution as seen in Figure 9-10(f) and Figure 9-13, that is monkeys in the lower ranking of `Dom` are preyed more than in the higher. In the case of the highest proportion of tolerants, seen in Figure 9-17(b), the distribution looks relatively flat. The tendency seems natural because the very despotics are aimed by the original DomWorld and the tolerants are not; however, it is still curious why their difference of nature has nothing to do with the death rate in spite of the difference of the troop construction (see Figure 9-16).

Figure 9-18(b) brings the difference from the case of egalitarian (refer Figure 9-14) into daylight[3]. The dominance ranking where the number of despotics is minimum is more than mean value in the case of tolerants (Figure 9-18), while approximately mean value in that of egalitarians (Figure 9-14). Additionally the distribution curve is almost linear in lower region than the dominance rank of the minimum number of victims in the graph for tolerants (Figure 9-18) although the curve is almost symmetry for egalitarians (Figure 9-14).

History of `Doms` for all monkeys are illustrated in Figure 9-19; it, however, does not look different with egalitarians' (Figure 9-15) very much. The number of dominance interactions by tolerant monkeys is less than that of despotics, as a result the `Dom` of egalitarian is apt to stay the periphery of its initial value.

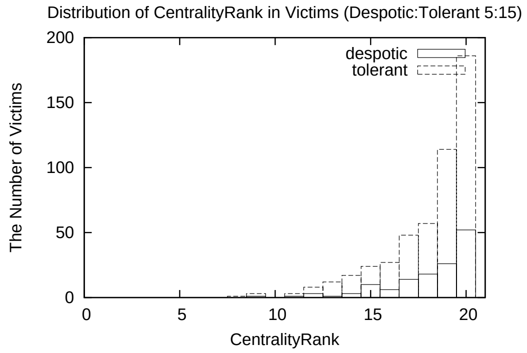
9.4.4 Summary of All Experiments

Lots of experiments have been conducted so far and all their results are summirised in Figure 9-20.

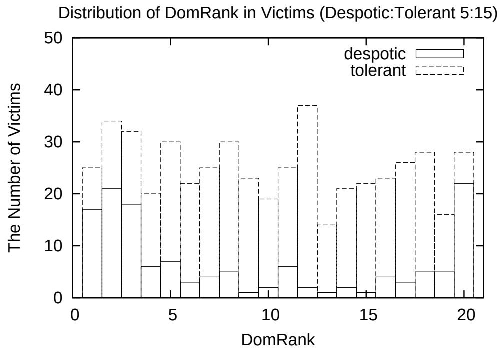
9.4.5 Consideration

What Leads To The Difference Between Results Of Two Compositions? The result about the egalitarians' case can be comprehended. Difference of effect of dominance interac-

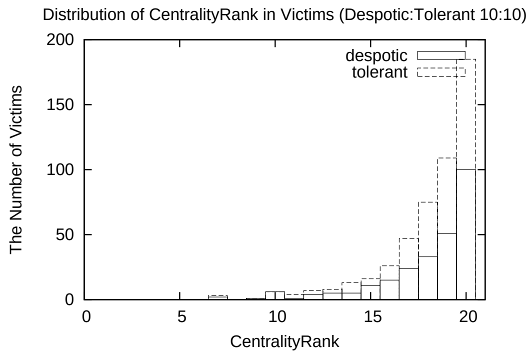
[3]The same tendency can be seen for all other compositions.



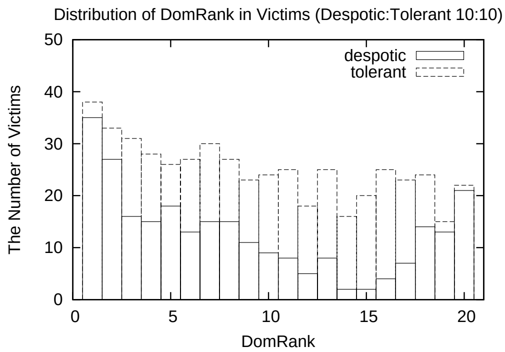
(a) Victim's Centrality Rank for 5/15



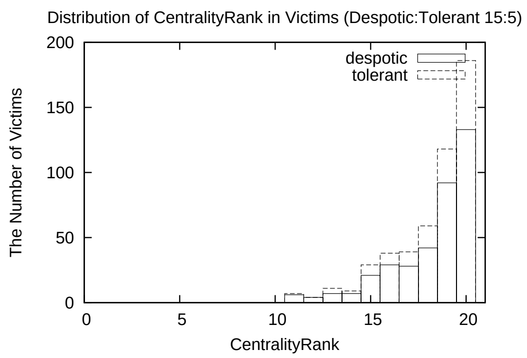
(b) Victim's DomValue Rank for 5/15



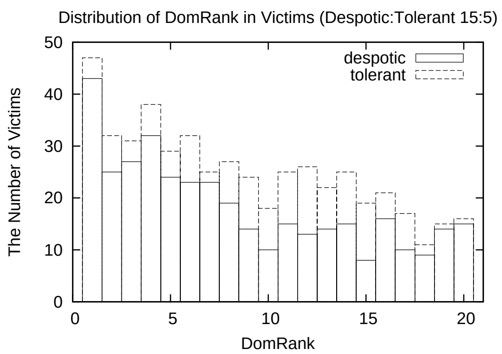
(c) Victim's Centrality Rank for 10/10



(d) Victim's DomValue Rank for 10/10

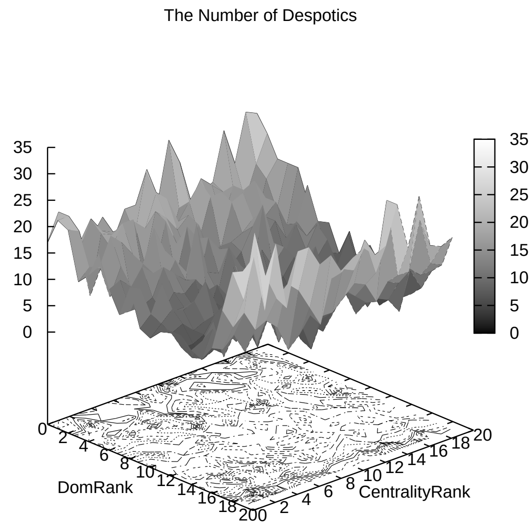


(e) Victim's Centrality for 15/5

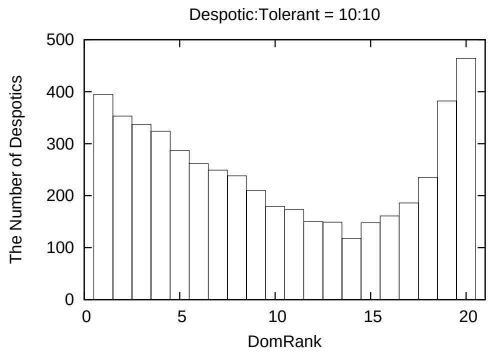


(f) Victim's DomValue Rank for 15/5

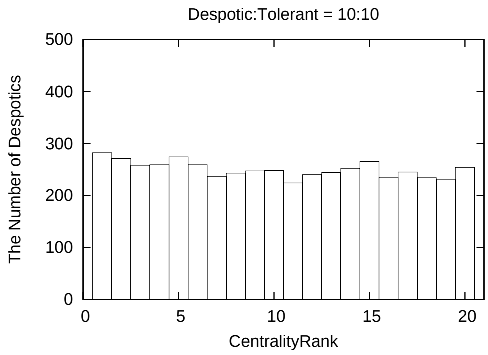
Figure 9-17: The Detail Of Victims (Despotic vs. Tolerant)



(a) The Number Per Combination Between Dom And Centrality



(b) The Number Per Dom



(c) The Number Per Centrality

Figure 9-18: The Sum Of Despotics' Status When Attacked By A Leopard (Troop Composition: 10 despotics and 10 tolerants)

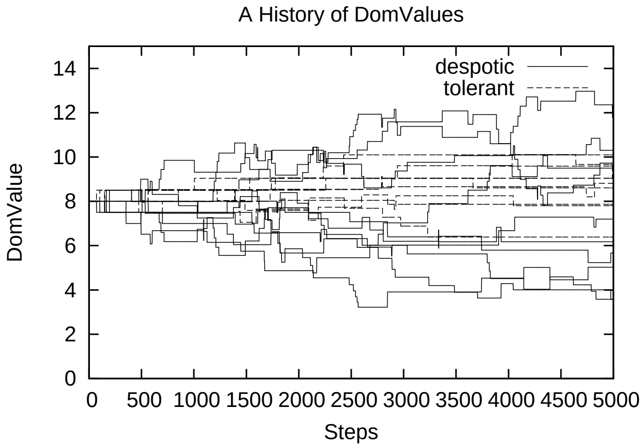


Figure 9-19: Typical Progress of DomValue (Troop Composition: 10 despotics and 10 tolerants)

Experiments	Conclusion
Confirmation of Being DomWorld	
Fierce vs. Mild	
1 The history of DomValue of Fierce Species	These six results agree with original DomWorld, so that the model constructed in the dissertation is a kind of DomWorld.
2 The history of DomValue of Mild Species	
3 C.V. of Both	
Loose vs. Cohesive	
4 The history of DomValue of Loose Species	
5 The history of DomValue of Cohesive Species	
6 C.V. of Both	
Modelling Vigilant Action	
7 The number of vigilant actions per centrality ranking	The more periphery a monkey is in the more vigilant it is
8 The number of vigilant actions per dom value ranking	The less dominant individuals are the more vigilant it is
Effect of Dominance Interaction on Being Eaten	
9 The direction of dominance interaction	Dominance interactions tend to be inward.
10 Relationship between DomValue and centrality	The more dominant a monkey is the more central it is in
11 Without Dominance interaction	Fringe is much dangerous to be eaten than the center and dominance interactions make dominant individual be in more centre.
12 With Dominance interaction which does not change dom	
13 With ordinary dominance interaction	
Effect of asymmetric dominance interaction on being eaten	
Despotic vs. Egalitarian	
14 The proportion of despotics to egalitarians in victims	Despotic is more dangerous than egalitarian.
15 The number of victims per combination between dom and centrality	Despotic occupy the central and fringe, while egalitarian in moderate position.
16 The number of victims per dom	
17 The number of victims per centrality	
18 The history of dom	
19 The detail of victims	
Despotic vs. Tolerant	
20 The proportion of despotics to egalitarians in victims	Both species are dangrous to the same extent.
21 The number of victims per combination between dom and centrality	The central position is occupied by despotics, while other position is shared by both species.
22 The number of victims per dom	
23 The number of victims per centrality	
24 The history of dom	
25 The detail of victims	

Figure 9-20: The Summary of Experiments

tion between two species (despotic and egalitarian) results in dispersed dominance values for despotics and those of convergent for egalitarians (refer Figure 9-14). Because predation tends to trim the lowest dominance valued individual despotics, which are apt to occupy extreme `Dom` values in both high and low value, fall victim to predation more than egalitarians.

On the contrary, the average ranking of `Dom` of tolerants is higher than that of despotics according to Figure 9-18. Additionally predominant monkeys tend to be in centre as stood by Figure 9-8 and 9-9. These facts logically lead to the conclusion that tolerants can carry through longer than despotics as egalitarians do, but their rate of being eaten is, nevertheless, almost equal to despotics (refer Figure 9-16). What is difference between the expected result of egalitarians' case and the unexpected result of tolerants'?

From the viewpoint of comparison with despotic, the similarity between egalitarian and tolerant is that the impact of dominance interaction on the whole is less than that of despotic. The whole effect depends on multiplication of the number of the interactions and the significance per interaction. The distinction between the two species is which element is different from despotics. In other words, egalitarians differ from despotics in significance while tolerants differ in the number.

What Is The Reason For Asymmetric Distribution Of Dom In Despotic/Tolerant Troop? In Figure 9-14(b) the distribution is asymmetric whilst it is symmetric in the case of despotic/egalitarian (Figure 9-18(b)). As stated in Section 2.2.4 there are two aspects of result of aggression in DomWorld: namely internal and spatial one. The former means varying of `Dom`. This is the subject of egalitarian. The latter indicates both the winner's going to the loser and the loser's fleeing from the winner. The effect is in proportion to the number of dominance interactions so that it is addressed by tolerant. In Figure 9-17(b) it is observed that the existence of tolerants disturbs the relationship between dominance value and centrality. This must come from the fact that tolerant ignores spatial effect of dominance interaction to some extent.

Because tolerants react to being attacked in usual way, they act as ordinary DomWorld monkeys toward their predominant so that they express their own nature only toward their subordinates. They never aggress to their subordinates; however, they answer the attack from predominants. The asymmetry of aggression is demonstrated in Figure 9-18(b). In the region where the ranking of `Dom` is relatively higher the tendency is similar to the graph seen in Figure 9-14(b) while in lower area it is completely different. Tolerants never contest against lower-ranked despotics; additionally lower-ranked despotics never attack higher-ranked tolerants because of prospects of losing in the attack. They are equal. So that the lower region of Figure 9-18(b) is almost linear.

Why Are Tolerants Threatened With Predation As Much As Despotics? As a conclusion the tolerant nature toward those of lower-ranking leads to different proportion of despotics in victims with that of in the composition of despotic/egalitarian (refer Figure 9-12 and 9-16). In DomWorld dominance interactions usually work as pressure to move attackers toward the centre of the troop in addition to the grouping rule (see Figure 9-8 and 9-9). Not only tolerant nature denies the advantage but also it accepts the disadvantage, which is being attacked. They are gotten rid of from central position and they never try to return the safer position. The fact rises the rate of being eaten of tolerants up to the same degree of despotics (Figure 9-12), which is higher than that of egalitarians (Figure 9-16).

Chapter 10

Discussion

In this section, all experiments carried out so far are discussed from the viewpoint of the effect of predation on the evolution of dominance hierarchy.

The experiments in Section 9.3 show that both centrality and dominance hierarchy affect being preyed by terrestrial carnivores. To speak more precisely only centrality has a direct effect on being eaten. The influence of dominance hierarchy on predation is subsidiary; actually the rank can influence only its positioning. It, however, can be regarded as a direct effect by the following reason. The results of experiments illustrated in Figure 9-10 tell that it has little to do with the positioning whether the dominance hierarchy is static, namely pre-defined, or dynamic, that is usual DomWorld. This may mean the variation of location for each member in a troop can follow the change of `Dom` for each quickly enough to avoid for transient location to influence being eaten. Accordingly it is valid that the effect of dominance hierarchy on predation is regarded to be at first hand.

The experiments concerning a mixed troop are executed in Section 9.4. Based on their fixed compositions there may not any alternative conclusion other than that egalitarian is disadvantageous to despotic (see Figure 9-12) and tolerant is equal to despotic (see Figure 9-16) from the viewpoint of being eaten; the results of same experiments, however, lead to completely different conclusion when inheritance of their ranking is taken into consideration. That is, predation can play a role to change social style to despotic in both compositions of troops. The reasons are expressed below.

In most of monkey species one gender stays in its birth troop and another leaves the troop when it comes at reproductive age probably in order to avoid inbreeding (Nishida & Uehara, 1999, ch.4). Because maternal society is much more popular than paternal in monkey society it is supposed hereafter that females stay in their birth group and males leave it; however, it should not be forgotten that the genders may be opposite in some species.

When a male joins other group after leaving his birth troop his rank is usually set the lowest in the troop. Then he repeats a dominance interaction to improve his rank in his lifetime. Unfortunately real strength of a monkey is equal to regarded dominance value in DomWorld. In other words the same value, namely `Dom`, is used both for anticipation of the result of interaction and for actual calculation of it (refer Section 2.2.4). In such situation it is extremely burdensome for incomers, who are set their rank the last, to promote themselves. If not the viewpoint of the initial ranking of an immigrant but that of the process of reassessment is made a point of, the assumption that a newcomer's dominance value is reset to initial value (but not the lowest) is valid. Then experiments in Section 9.4 may be appropriate to the case and the results are applicable as they are. Egalitarian males, which make light of the result of dominance interaction, are more advantageous to survive than despotics, so that it is likely that males gradually acquire egalitarian nature while alternations of generations are replicated. Regrettably, it cannot state about tolerants' contest against despotics at all because their death rates from predation are equal (see Figure 9-16). However, an unexpected but interesting knowledge can be extracted through the result. It is often observed that male is more tolerant of female than of the same sex. The one-sided tolerance likely causes no disadvantage in being eaten comparing with despotic, namely female in the case.

In most maternal societies the ranking of a daughter is assigned right after her mother. Under such circumstances the consequence differs from the case of male in spite of starting from the results of the same experiments. In the case that the dominance value is inherited not only the temperament of a victim but also its dominance value is important. From the perspective of temperament egalitarian nature is the most advantageous to subsist as the case of males; however, when the dominance values of survivors are paid attention to despotic character may be more beneficial than others from different point of view. In other words most dominant positions tend to be monopolised by despotics because they are split into two groups: high and low, and the members of the lower-ranking group are trimmed by predation (see Figure 9-13 and 9-17); accordingly only higher-ranking individuals can bear a child with regard to despotics. From the point of view, predation does not affect tolerant and egalitarian very much owing to the fact that their dominance values are not so dispersed as those of despotics.

In comparison of despotic females with egalitarian females it depends on the circumstances which temperaments result in dominant. Egalitarians are beneficial in the number of individuals earlier while despotics are advantageous in the position of dominance hierarchy later. Accordingly in the case that more than a certain number of despotics can survive at the first stage the despotics become ascendant, otherwise egalitarian become dominant.

On the contrary with comparison with tolerants it is clear that the despotics are advantageous to survive. They are in danger of being eaten to same degree (see Figure 9-16); however, while all individuals are evenly preyed in the case of tolerants only less dominant members fall victim in despotics. As a result despotics gradually occupy the dominant position and then the proportion of tolerants in victim is getting higher and higher; finally all member of a group must become despotics owing to annihilation of tolerants.

Taking advantage of the supposition discussed so far, the phylogenetic tree seen in Figure 9-11 is considered from now on. The figure is reprinted below for convenient.

First of all, Thiery divided in the grades according to patterns of aggression and reconciliation(Thierry et al., 2004, p.273), so that he might use the word, 'tolerant', in the almost same meaning of the dissertation.

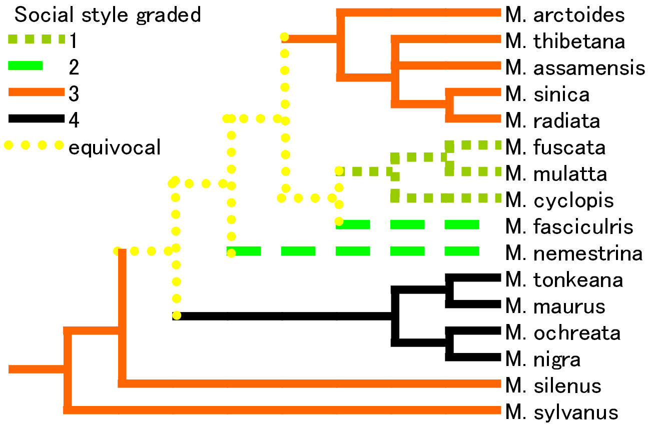


Figure 10-1: The Distribution Of Social Styles On A 4-grade Scale In Mapped Onto The Phylogenetic Tree Of Macaques (revised Thierry et al., 2004, p.284). Interindividual tolerance increases from one to four. (reprinted Figure 9-11)

Because the most primitive species belong to the grade 3 there are two ways for the social style to evolve. They are: to become rigid and to get to be slack[1]. These directions are considered respectively. With regard to the most rigid style (grade 4) the first characteristic is that it is the earliest style except for grade 3. Secondly once the style become rigid other style will not rise on the genealogy. When a troop consists of a little despotics and plenty of tolerants it is often observed that all of the few despotics become dominant or subordinate instead of split into two extremes. It amounts to this, that it is likely that fair tolerant society (represented grade 3) transfers fully tolerant society (stood for by grade 4). In addition once the style become fully tolerant it stays tolerant because in such society there are so few dominance interactions that incentive for social style to change does not exist in the model. Furthermore, even if it is not fully tolerant the style are kept under the circumstances that all of a little despotics are subordinate of most tolerants because lower-ranking despotics do not attack high-ranking tolerants. In brief fair tolerant society (means grade 3) possibly become fully tolerant (grade 4) and the grade 4 society seldom change any more. The fact seen in the model introduced in the dissertation agrees with the phylogenetic tree.

Then paying attention to becoming the style tolerant, it is noticed that the grade 1 of society emerges after the grade 2. Because the most primitive style is grade 3 the social style is said to become gradually tolerant. Moreover although it is just an expectation the grade 4 of society may be derived from the grade 3 supposing that the social style cannot change so sharply from grade 3 to 1. The fact seems to agree with the result of experiments that the social style of staying gender gradually becomes despotic (see former part of the section).

As a conclusion the results of all experiments done in the dissertation do not conflict actual data. Although additional data to verify should be collected it is likely that predation affects

[1]Although there is one more way, namely to stay the grade 3, it is ignored from the point of view of evolution.

the evolution of dominance hierarchy so far.

Part IV

Conclusion

Chapter 11

Future Work

Though some achievements in both development and research have been accomplished so far, there are things left which should be done in future; some are scheduled but uncompleted works and others are those of newly detected from the achievements. These future works are stated on two realms respectively.

11.1 Framework

The most significant point to improve in the framework is its performance. Regrettably the execution on the framework is far from quick. Although a evolutionary modelling may be desirable in order to progress the experiments with taking advantage of current results the framework may not be able to stand enormous repetition to reinforce the composition of a troop for the moment. Some core functions should be implemented on C/C++ language in spite of dependence on operating system.

The advanced action selection addressed at the very beginning of design has not finished yet. Current agents decide their behaviour according to hard-coded process so that experimenters need to rewrite the code directly when they want to try another model. The rewriting is not so demanding in Smalltalk because of its fusion of a runtime environment and a development environment but nevertheless a better way should be offered. One of solutions is tile scripting named eToy, which is graphical programming environment pre-installed on Squeak. This allows programming on Squeak without knowledge of Smalltalk (e.g. Appendix A.); however, available control sequences in it are not very rich. Obviously it should be expanded for practical modelling. Bryson suggests POSH (Parallel-rooted, Ordered Slip-stack Hierarchical) reactive plans (Bryson, 2001). In POSH there are three types of plan elements: action patterns, competences, and drive collections. These control sequences seem the very lacking features for eToy as an individual-based modelling tool. In addition the idea is quite compatible with eToy. It must be effective to develop tiles representing the three and to make agents behave according to tile scripts composed with the POSH tiles.

As stated in Section 2.3.1 visualisation is important for MAS simulator and an operable 3-

dimensional view is often one of the best ways to convey complicated information. The current version of the framework can handle only 2D view although there is a sophisticated 3D library called Alice in Squeak. In near future the framework may become able to deal with 3D model taking advantage of the Alice. The appearance of the prototype can be seen in Figure 11-1.

Figure 11-1: 3D Version Of DomWorld

11.2 Experiments

From the viewpoint of investigation into the effect of predation on primate society, it is most important to collect much more available data. Though the results of the experiments suggest possibility that predation affects the evolution of primate society only actual data can confirm it.

There are at most two tendencies in a troop so far. These tendencies are defined by variations of a few properties, namely `InitDom`, `StepDom`, and `PerSpace`. Providing these properties are made variable and individually vary little by little in their life time according to a certain rule, what happens on the social structure? In addition, if the values are inherited from parents and a troop is observed down the generations more interesting knowledge must be obtained.

A monkey behaves toward all other monkeys in the same way; however, it is natural that the result of former interaction with an opponent affects the decision how it acts to the opponent. Even if a monkey has tolerant nature it may make a pre-emptive attack against the opponent which is previously attacked it. If agents can memorise all attacks suffered by others and change their behaviour according to an opponent based on the memory it can be investigated how the introduction of a few particular natured agents infects with all other agents. The result must be utilised for analysing transformation of social style.

When monkeys detect a predator they always flee in the model although actual monkeys have a lot of anti-predator behaviours as stated in Section 2.1.4. Above all things the mobbing feels interesting because it is likely that the behaviour affects monkey's coherency (i.e. the size of a monkey's `PerSpace`). More intimate investigation can be done by implementing anti-predator behaviours varied according to its situation.

In the dissertation only terrestrial carnivore is addressed in spite of the fact that various predators aim at monkeys (see Section 2.1.4). Each kind of predator can affect a monkey troop in different way. For example, raptorial must have another influence on primate society from a leopard because it can target even the central individual. It may set off the disadvantage of monkeys in fringe by terrestrial curnivore; accordingly, it is likely predation as a whole has no effect on the hierarchical structure of a primate troop. In order to estimate the effect by predation the existence of a variety of predators is compulsory.

The dissertation reveals that a winner's chasing and a loser's running away take an important role in the original DomWorld; however, the algorithm is decided based on not a realistic observation but a practical reason (i.e. to avoid successive interactions). It should be revised for a more realistic model of monkey siciety.

Chapter 12

Summary

At first a MAS simulator is developed in the dissertation. The chief characteristics are: making the most of Smalltalk itself, allowing experiments being executed as simple as possible, and making it easy to construct a new experiment. Satisfaction of them and advantages of the framework are demonstrated by the fact that more than ten kinds of data can be derived in less than one month by utilising the framework. Unfortunately there are some problem mainly about performance and incomplete tasks. They are all reserved for future work.

With regard to the thesis the results are positive about the probability that predation affects the evolution of dominance hierarchy in primate society. To be specific, it is likely predation by land carnivore is apt to make their society more despotic. Supplementally some additional knowledge about DomWorld is obtained. An aggression tends to be done by outer individual to inner one (Figure 9-8); probably as a result of it there is a positive correlation between centrality and dominance value (Figure 9-9). However, the aspect of DomWorld may be in need of being improved, as stated in Section 11.2.

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Appendices

A: Prototyping by Tile Scripting

As stated in Section 2.3.2 there is a graphical programming environment called eToy on Squeak. Despite the fact that it is mainly aimed for kids it is so powerful that it is useful for the earnest application. In the author's view, the eToy is quite suitable for prototyping or introduction for novice in Smalltalk because the script constructed on eToy can be transformed to corresponding Smalltalk expressions.

In this Appendix the procedure for building a simple behaviour (simplified Boids (Reynolds, 1987)) on eToy is demonstrated by utilising a lot of figures in order to provide the image of the tile scripting. Most of functions illustrated in the Appendix depend on the power of Squeak itself although some of them are expanded for the dissertation.

First of all, the simulator is started without any preference.

```
BoidWorldSimulatorWindow new openInWorld.
```

When the button named 'breed a boid' in 'Boids' tab is clicked a dialog to input a species of the created boid is opened (see Figure 12-1).

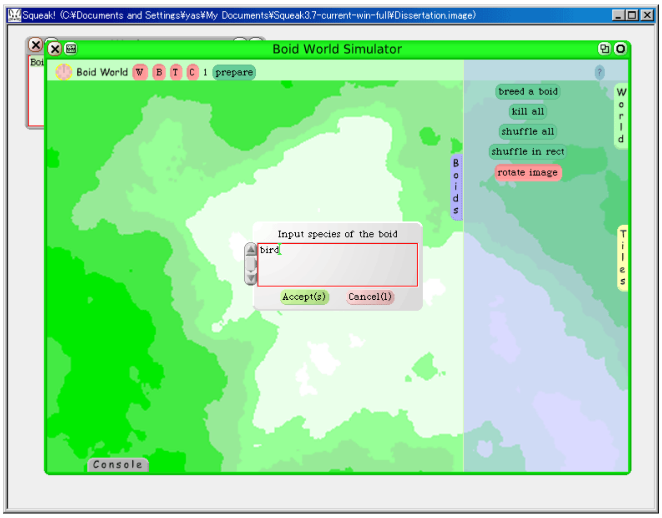

Figure 12-1: Input Species

As soon as the species is accepted (now it is ‘bird’) the script editor is opened (see Figure 12-2).

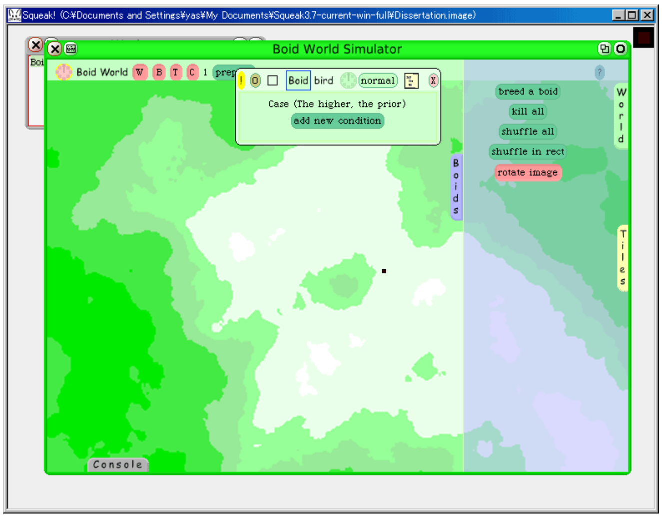

Figure 12-2: Initial Script Editor

Then ‘add new condition’ button is clicked three times to add conditions corresponding three rules of a boid (i.e. separation, alignment, and cohesion (Reynolds, 1987)). After that each condition is set as Figure 12-3.

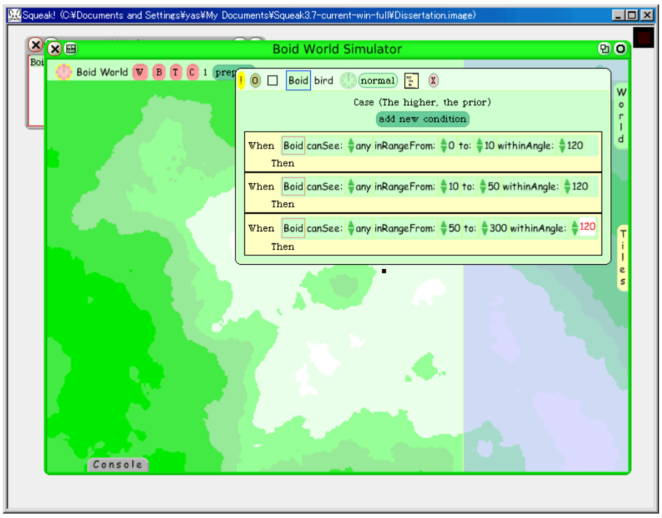

Figure 12-3: Add Three Conditions

The tiles for actions corresponding each condition are put at 'Then' areas (see Figure 12-4).

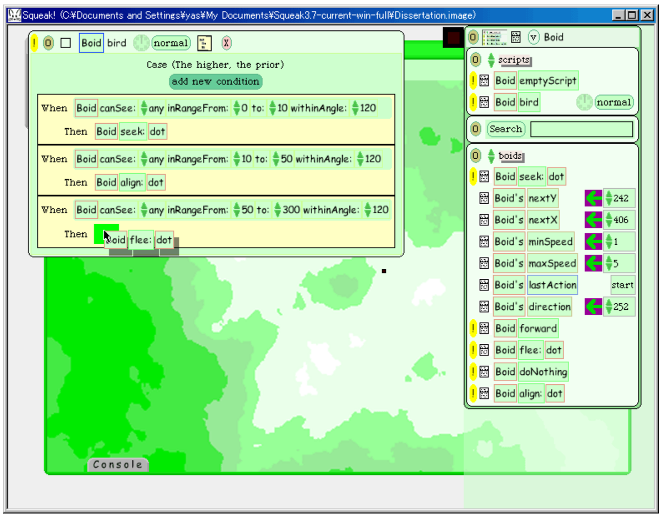

Figure 12-4: Set Behaviours

Each behaviour is completed by using special tiles for the dissertation on 'Tiles' tab (see Figure 12-5). Now the behaviour of the bird is defined as following: when a neighbour is too near it aparts from the neighbour, when it can keep moderate distance with all other birds it aligns its speed as the gravity of others, and when any neighbour does not exist it tries to approach the nearest.

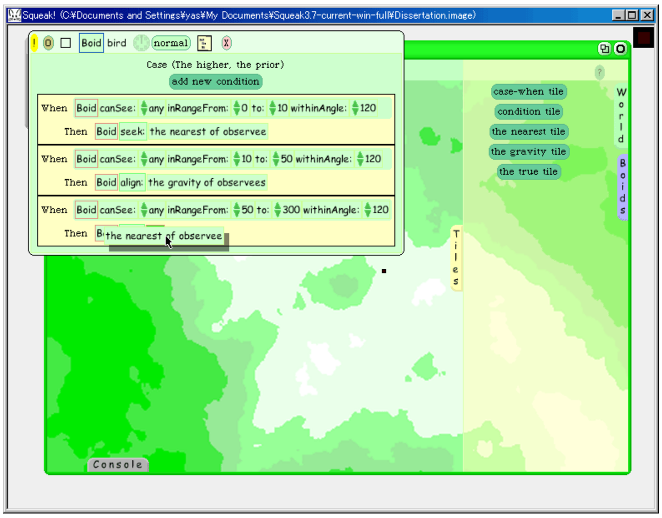

Figure 12-5: Complete Behaviours

Because all works the scripting editor is finished it is hid by clicking ‘o’ button (see Figure 12-6).

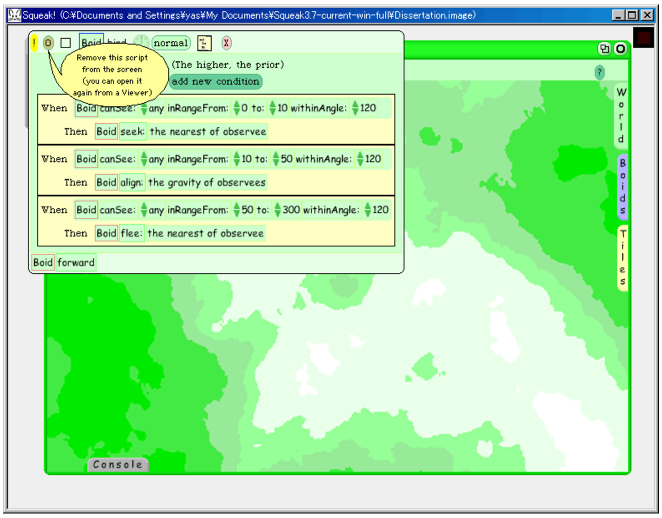

Figure 12-6: Close Script Editor

The behaviour of the bird is set up now. Hereafter the appearance is made like a bird. In order to change its appearance call its halos and click gray (repaint) one (see Figure 12-7).

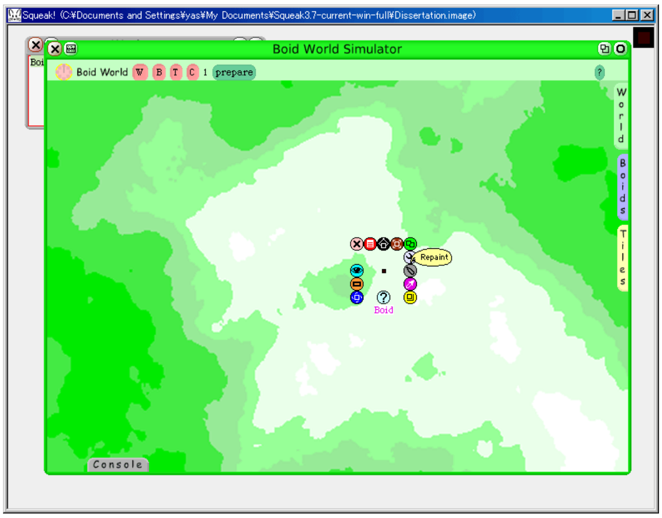

Figure 12-7: Call Halos

Clear the original appearance and paint a bird (see Figure 12-8).

Figure 12-8: Draw A Bird

Adjust the size of the bird with yellow (change size) helo (see Figure 12-9)

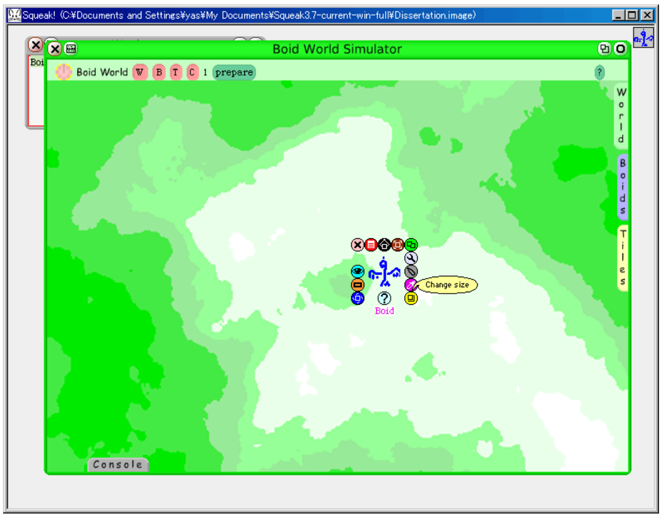

Figure 12-9: Change The Size

Click ‘breed a boid’ button five times so that there are six birds altogether. If the species has existed in the world its appearance is automatically set the same as the progenitor (see Figure 12-10).

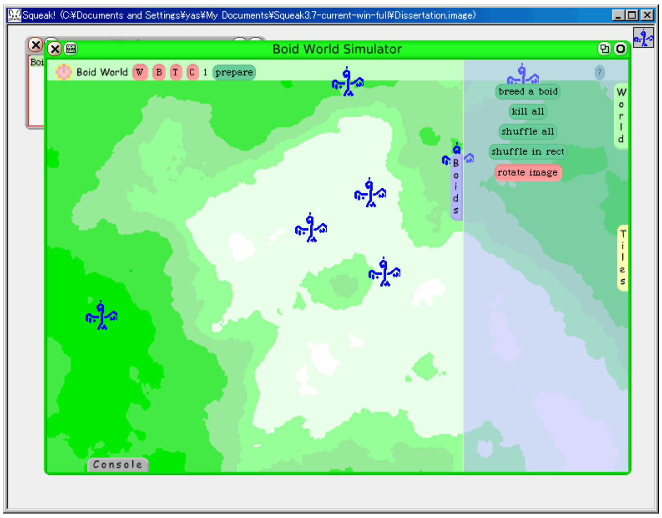

Figure 12-10: Make Copies

Initial location is too dispersed to make a flock so that they are gathered by ‘shuffle in rect’ button in ‘Boids’ tab (see Figure 12-11).

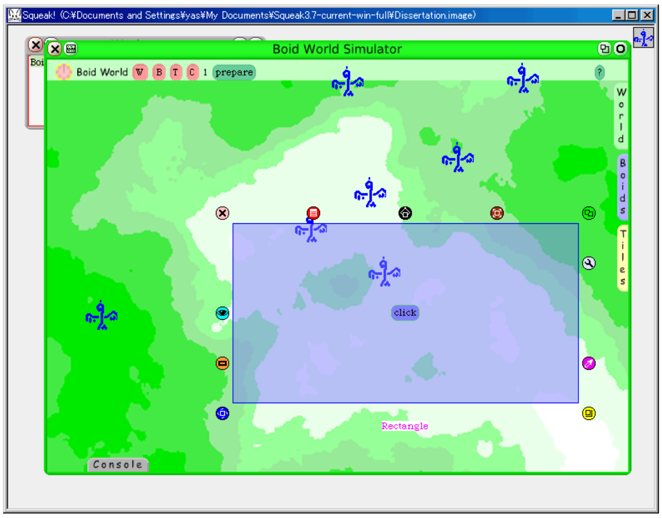

Figure 12-11: Collect Birds

Start the world timer (see Figure 12-12).

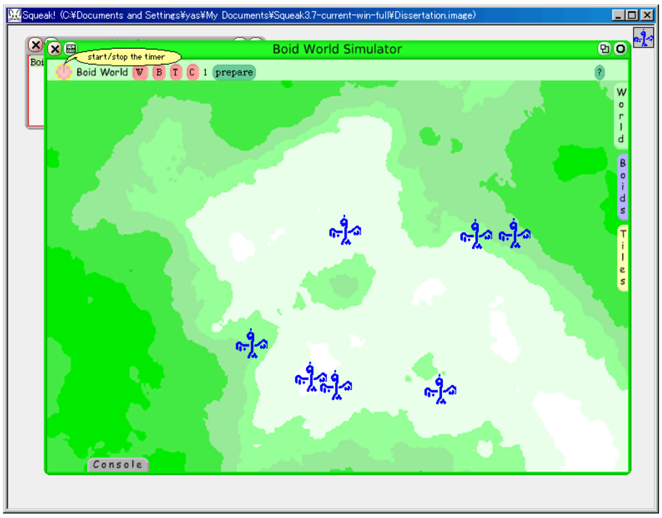

Figure 12-12: Start Timer

Then they make a flock according to the rule defined upwards.

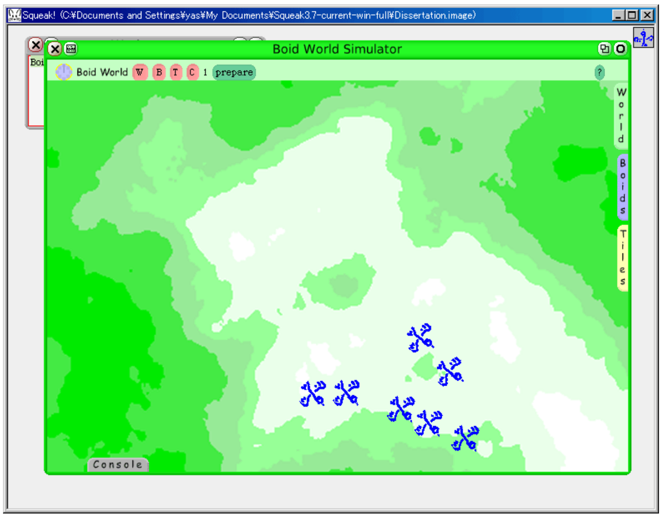

Figure 12-13: Flocking

B: Code Listing

Although principal codes are attached below, there are some noticeable points peculiar to Smalltalk. Please remind what are accounted below while you read codes.

The format of codes are called 'chunk file', which is generated by Smalltalk environment. Unlike other major programming language, codes of Smalltalk are intended to be programmed not on a text editor as a programmer likes but on Smalltalk environment. In other words the codes do not aimed to be printed out nor to be read in sequential way. Please accept the difficulty of the codes to read.

As stated in the body of the dissertation Smalltalk environment is so good to look around codes that traditionally Smalltalker, a nickname for a programmer of Smalltalk, makes light of comments. Rather, too many comments are regarded a sign of poor design of the code (Fowler et al., 1999) because it means that the code is too complicated and difficult to understand without such plenty of comments. Newcomers in Smalltalk world notice the fact as soon as they try to read existent codes for the system. In compliance with the tradition, there are not very much comment in the code. I am hopeing readers will respect the convention.

'_' is displayed as a left arrow sign (←) in Squeak and it means to assign a concrete value into a variable. That is, it can be exchanged with ':=', which is used for an assignment in other Smalltalks.

Boid-Kernel Category

Boid-DomWorld Category

BoidPlayerTest