Natural and Artificial Systems: Compare, Model or Engineer?

Kelly Vassie[1] and Giuseppe Morlino[2, 3]

[1] Unaffiliated, London, UK
kjvassie@ed-alumni.net
[2] Computer Science Department, Sapienza University, Rome, Italy
[3] Institute of Cognitive Sciences and Technologies, CNR, Rome, Italy
giuseppe.morlino@istc.cnr.it

Abstract. Some areas of biological research use artificial means to explore the natural world. But how the natural and artificial are related across wide-ranging research areas is not always clear. Relations differ further for bioengineering fields. We propose a taxonomy which would serve to elucidate distinct relations; there are three ways in which the natural is linked to the artificial, corresponding with distinct methods of investigation: i) a comparative approach (natural *vs* artificial) in which artificial systems are treated in the same way as natural systems, ii) a modeling approach (natural *via* artificial) in which we use artificial systems to learn about features of natural ones, and iii) an engineering approach (natural *pro* artificial) in which natural systems are used to draw inspiration for artefacts. Ambiguities about and between these approaches limit the development of fields and impact negatively on interdisciplinary communication.

Keywords: Artificial Life, Extended Mind, Thought Experiments, Modeling, Bioengineering.

1 Introduction

Distinction between two kinds of synthetic approaches to biology – i) comparative, such as ALife or Evolutionary Robotics and ii) the more widely known (and understood) modeling practice – are not entirely new. These approaches have previously been separated on the basis of: clarity or complexity [1]; methodology (Miller 1995 cited in [2], [3-5]; abstractness [6]; and as different levels of enquiry [7-8]. There are implicit arguments about the relationship between natural and artificial underlying each of these distinctions but these considerations are not seen as important. For example, in [5] Harvey et al. argue that Evolutionary Robotics (ER) 'is a new scientific tool', insofar as the methodological emphases (minimal cognition, existence proofs and reduction of bias) are very different from modeling. They claim that ER 'systems will not tell us how real cognitive systems work' whereas, for example, neuroscientific models might [5]. It is clear that the artificial system in modeling stands in for the natural system – because results about the model tell us how natural systems work. Yet it is not always clear how the ER system relates to a natural system. This is evidenced for example in the discussion of an ER simulation study into the origins of learning (Tuci et al. [9] cited in [5]). In this experiment some mechanisms for learning emerged, although no hypothesis could be made for these kinds of processes or the architecture that would support them – otherwise it could not be a study into the origins of learning itself. The learning mechanisms cannot be evidence for a natural system because the methodological processes have not specified a target system for this purpose, as modeling a learning mechanism would do [5]. What this ER experiment did show is that while an organism can evolve processes which enable it to learn, the actual mechanisms that emerged can only be used to help build concepts about learning. The relationship between natural and artificial in such work is not explicit; this has resulted in a negative view of simulation approaches. For example, Webb argues in [7] that because theoretical proofs eventually require comparison to the natural world they are basically a class of model, and if they don't represent anything "real" in the natural world they are (or should be) irrelevant to biological investigation. The issue for simulation work, if Webb's argument is accepted, is that it would be evaluated against the same requirements as modeling – justifying work on the basis of a concrete fit to empirical data [1], [7]. As we have just shown it is not empirical data that is generated but ideas about what mechanisms might be, and proof that learning can evolve from simple mechanical components. The outcome forced by Webb would not enable ALife researchers to develop scientific practices or revise relevant biological concepts (see [4] for an example), both of which are important for the advancement of this newer field. Furthermore, given the possibility that life *might* be artificially created, we would need a structure for the analysis of this artificial system because the artificial would have the same characteristic as a natural system, making it distinct from the representative characteristic of a model.

These two distinct relationships between the natural and artificial each give rise to their own epistemological concerns and considerations. One important concern is that the processes of simulation work in ways that go beyond (or abstract away from) our cognitive abilities. The argument that the non-anthropocentric process of simulation requires different epistemological considerations follows Humphreys (see [3]). Humphreys has different arguments from the one we present here, but we do have similar conclusions – that a "new-analysis" of the relation between artificial and natural is necessary, and that this includes making their epistemological concerns distinct. Our paper provides a structure for this analysis to take place.

As well as aiding the development of newer fields we see our work as providing an important framework for interdisciplinary communication. In light of the evergreater specialisation within science – and, conversely, the rise of collaboration – our taxonomy offers a new tool for assisting professional dialogue and public science engagement. It is in this spirit that we include clarification of how the developing fields of bioengineering relate to the epistemological approaches of comparison and modeling. Finally, following Cordeschi [10] our intention here is not to carve unnecessary boundaries between approaches and opposing paradigms (i.e. we think that both comparative and modeling work is important, and within them, work from different kinds of theoretical positions).

2 Comparative, Modeling and Engineering Approaches

In the following sections we outline the three approaches – natural *vs* artificial, natural *via* artificial and natural *pro* artificial – discussing the role of artificial systems in each. Figure 1 provides a context for this taxonomy.

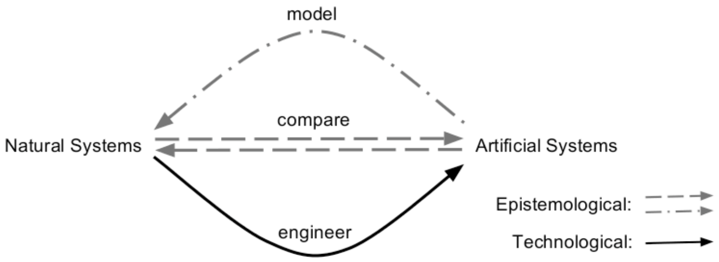

Fig. 1. Diagram showing the use of natural and artificial systems (arrows depict direction of system use)

We will show that the difference between comparison and modeling also concerns different levels of explanation and experimentation. We then argue that as the relation between the natural world and the artificial system is different, the epistemological issues must also be different. Further distinction will then be made between the epistemological (scientific) approaches of *vs* and *via*, and the engineering (technological) one of *pro*. We explain how the relationship between natural and artificial is reversed in these engineering approaches; even though models can be physically built as artefacts (albeit using engineering techniques), the aim of an actualised model is still the *explanation* of a natural phenomenon. However, before we outline these approaches we need to disambiguate the use of “simulation” to avoid confusion between simulations as used in the comparative approach and the simulation techniques used in modeling and engineering: in the comparative approach (*vs*), simulations are artificial systems used to build theories, question assumptions and explore mechanisms (as in ALife); in the modeling approach (*via*), simulation is used to animate the model. Once a model –

representing a natural system – has been developed, the simulation – representing the operation of the model over time – can act as a descriptive or predictive tool. Finally in engineering processes (*pro*), simulations are rich in detail and used to trial technologies for economic reasons; they are a more efficient test than expensive hardware prototypes.

Comparing Systems: Natural *vs* Artificial. Comparative (animat) approaches[1] to science investigate the origins and mechanisms of phenomena. In treating artificial systems like natural ones we can deepen our understanding of nature, gain further insight, or develop a new means of problem-solving – for example Webb notes that comparing a heart to a pump has an explanatory value distinct from modeling the process of blood circulation or creating an artificial heart [7]. The value lies in the pump being a kind of *source model* – usually seen as an artificial system that exists independently of the target system or hypothesis (i.e. the pump became a model for circulation after its creation) [7]. It is also common in the animat community to work with artificial and natural systems simultaneously (i.e. comparing the artificial and natural processes against each other in real time, see [11] for an example). Thus comparison does not stop at treating artificial systems like natural ones; the term 'compare' implies that there is value in noting the similarities *and dissimilarities*. The *vs* approach *can* then be seen as a two-way explanatory relationship between the two kinds of system; which would have methodological similarities with ethological practices (e.g. [8]). Furthermore, this relation allows all possible similarities and dissimilarities to be addressed– i.e. counterfactual analysis. Under this approach we would identify at least *two* important kinds of experimentation. The first is *thought experiment* – 'devices of the imagination used to investigate the nature of things' [12]. Thought experiments have no accepted definition but are widely held to be a useful method for highlighting inconsistencies in theories and building intuitions [2]. A famous example of a thought experiment is Schrödinger's Cat. The experiment shows that a quantum system (a cat in a box with various items including a radioactive substance) can be in two states at once (a superposition), because until you open the box and observe whether the radioactive substance has decayed, there is no other option but to hold that cat is both alive and dead.[2] Secondly, we are introducing the notion of *extended experiment* to link the aims and methods of comparative approaches with those of the Extended Mind Thesis (EMT hereafter, [13]).[3] We see affinity between comparative approaches, which can promote understanding and allow new means of problem solving, and EMT, which holds that

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[1] We use the term "comparative approach" instead of the commonly used "animat approach" to show one alternative way to understand and explain the place of ALife in the biological sciences.

[2] In separating thought experiments from ALife simulations we are agreeing with Wheeler that 'ALife models are not thought experiments – philosophical or scientific'[14].

[3] See Humphreys [3] for an alternative (non-embodied) approach to defining hybrid investigations.

artefacts can be tools for thought – because they can function as, and therefore enhance, our cognitive processes. EMT holds that the physical mechanisms of our thinking extends beyond our biological boundaries when a two-way relationship between cognitive and external systems exists – for example using a smart phone as an external memory store, or a notepad to work out a sum [13]. Thus extended experiments can also be extended systems (as defined by EMT), because cognitive processing is enhanced and distributed across biological and technological boundaries: in devising new theories we're doing so with the additional processing power of technology, but it's a reciprocal relationship because our biological processes are necessary to make sense of a scientific experiment. An important outcome in viewing the process and evaluation of simulation work in this way is that "experiment as a tool to further understanding" underlines the distinct scientific character of simulation and the two-way relationship between natural and artificial. It has been argued that simulation experiments have no scientific value (reported by Di Paolo et al. in [2]): they are seen merely as computer programs in which symbols are re-arranged logically and as such cannot give rise to new knowledge. However, given that in our taxonomy extended experiments can be tied to cognitive processes as tools for problem-solving, they can be more than "just a computer program" – they can be part of a process which facilitates conceptual development. Therefore, extended experiments do not *test* concepts; rather, they *come up with* concepts, aiding the (re-)formation of concept and theory. ALife holds a special role within this context because it i) serves as a bridge between disciplines [14], [16], ii) allows phenomena to be described in abstract terms [1] and, iii) helps us derive intuitions about life [2].

Evolutionary Robotics, like the origin of learning study mentioned above, is full of experiments that can be viewed as comparative (see also [5], [15] and [17]). Similarly, Ponticorvo and Miglino's work [4] compares a simulation with a variety of natural behaviours. Their research aims for *insight* into the many potential mechanisms that cause spatial behaviours, in order to create "theoretical proof" – backing up the intuition that mechanisms of orientation behaviours in natural systems do not require a modular neuro-cognitive system. Importantly, they conclude that modeling work would be needed to provide "actual proof" for spatial mechanisms [4]. Consequently the study can be seen as effective if it aids cognitive processes for a re-conceptualisation of spatial behaviours in natural systems, as opposed to providing actual evidence that architecture *is* non-modular. The epistemological concerns here are centred on how the artificial is compared to the natural at different stages of investigation, how results relate to theory or intuition about a natural phenomena, and how we learn from processes we cannot fully access.

Modeling Systems: Natural *via* Artificial. Scientific models can be conceptual, computational, or mathematical representations of nature. The empirical inquiry surrounding modeling centres on how closely a model "applies" to anything in the world so as to be a useful prediction or explanation [7]. Once the model is said sufficiently (or perhaps roughly) to predict or explain something, the hypotheses are said to be true [1]. The degree to which 'the hypothesis accounts for existing data and predicts new data from observations on the target phenomenon is taken to support its status as an explanation' [7]. Cordeschi explains further: 'The artefact therefore embodies the explanatory principles (the hypotheses) of the theory and is considered a test of the theory's plausibility' [10].[4] However, the hypothesis is only associated with a simplified or narrow element of the natural system, factoring out unrelated phenomena, to make analysis possible [10]. The process of modeling as a whole is the process of creating a representation of a target phenomenon, testing this artificial system, and evaluating the success against evidence about the target system: the artificial system models the natural – this is as depicted in Figure 1.

An inclusive account of what constitutes a model is required here so that more general or conceptual work is permitted. One such account is Barandiaran and collegues's [18-19]; they propose that there are four types of modeling distinguished by their degree of abstraction: *mechanistic*, characterised by an almost one-to-one correspondence between variables in the model and observables in the natural system; *functional*, which aims for behavioral or functional (rather than a variable-to-variable) correspondence between the model system and the target natural system; *generic*, covering a wide spectrum of phenomena in search for generic principles of complex systems; and *conceptual*, which do not target any particular natural system nor a collection of them – they are built from theories. As such conceptual models illustrate concepts by representing theoretical principles [18]. Despite the abstract nature of the latter two modeling types, the process of an artificial system standing in for the natural remains common, allowing an exploration of a biologically founded hypothesis, which is subsequently evaluated on the strength of its ability to predict or explain the target natural systems or natural phenomenon. Models can also be used as metaphor to support justification. There are thus different levels of explanation and investigation: the construction of the model, the analysis of the model, and the way that the model is used to aid explanation.

The epistemological concerns within the modeling approach – how we learn from models – have a complex history (see [10], [20-21]), especially in light of new debates on how modeling differs from ALife simulation [1], [14]. In modeling, the natural phenomenon is related to the stages of designing, building, manipulating and evaluating in different ways [20]. The scientific process and the epistemological processes are thus intricately linked – and there are two key arguments for this interconnection. According to Hughes [20] there are three stages involved in gaining knowledge from modeling. These are denoting (which links a theory or hypothesis of a natural system to the building of the model), demonstration (connecting the natural system to the representative model) and finally interpretation (linking the success of predictions to the explanation of the natural phenomenon). On Hughes's

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[4] To clarify, we're not arguing for a specific view on the relationship between model and theory we mean to show that the structure provided here can accommodate various positions.

view there are three clearly defined relationships between the model and the target system – which should hold for any level of abstraction. Another influential, and similar, view comes from Morgan. Her argument says that we learn from models in two ways – from building them, and from manipulating them – but it is the "representational mechanisms" involved which underlie both [21]. From both Hughes and Morgan, the representative essence of modeling provides the foundation for epistemological gain, and subsequently for philosophical debate.

Engineering Systems: Natural *pro* Artificial. Engineers use natural systems to develop novel solutions to engineering problems and to construct technological artefacts; the artificial system in this approach is then the output of the process. Alongside the epistemological levels of *vs* and *via* there is a further "level" distinction – between epistemological approaches and technological approaches. A key characteristic of technological work is the separation of design and fabrication [22]. This *pro* approach includes, among others: *bioengineering* – taking what we know of natural systems and adapting it for the development of new engineering solutions. This kind of approach is widely used in synthetic biology; *biomimicry* – directly copying nature to create new technologies; and *natural computation*, incorporating the use of natural systems to develop alternative problem-solving techniques, the use of computers to synthesise natural phenomena, and the use of natural materials to compute [22]. Alongside electronic hardware, computation can be implemented in a range of media (e.g. silicone).

An example of bioengineering is Micro-Aerial Vehicles [24] – small, insect-like flying devices developed for robustness and efficiency. Applications include video surveillance, weather mapping and military surveys. An example of biomimicry is the creation of buildings that copy the structure of termite mounds for a more efficient, cheaper means of air circulation than air conditioning [25]. Meisel et al. in [22] classify the many types of naturally-inspired computation, including cellular automata, neural computation, evolutionary computation, swarm intelligence, artificial immune systems, membrane computing and amorphous computing.

3 Differentiating Epistemological Concerns

We have just outlined how comparison and modeling are distinct – based on how each approach uses artificial systems to learn about natural ones. In this section we develop this argument, showing that what follows from this are two distinct sets of epistemological concerns. We then differentiate engineering practice.

The separation of the way that simulation and modeling relate to natural systems is important for *four* key reasons. *One*, comparative experiments have been seen as unscientific because their relation to natural systems is not easily defined, as it is in the more established approach of modeling. In modeling the explanandum is clearly stated at every stage but in extended experiments it might not need to be. This would mean embracing the difference between a model and a source model (see section 2):

the model relates to a pre-specified natural phenomenon at all stages of investigation, whereas simulation is allowed to be separate, or perhaps more "opaque" – as in the way Di Paolo et al. mean in [2]. With proper foundations for separation, ALife can grow as a field and define its own scientific methods and processes. New kinds of experimental work might be permissible under this distinct approach. *Two,* following these "unscientific" criticisms, the evaluation stage of simulations has been seen as unsuccessful when assessed against modeling criteria. So, contrary to Webb [7], the epistemological value of a study using artificial means cannot be measured solely on the basis of its direct impact on reality (or on data generation) – because this does not relate to experimentation within the comparative approach – which can allow counterfactual analysis and foundational explanations [26]. *Three,* this taxonomy facilitates interdisciplinary communication. In clearly defining the investigation within a specific approach other researchers can access the work of fields vastly different from their own. This might be useful, for example, given that thought experiments are in the same category as ALife simulation: some of the philosophical literature on thought experiments might help the development of Alife [1]. Better foundations for communication would also aid research across related fields: paired together, practitioners of ALife and economics, say, or neuroscience and ecology, might see structures and patterns in practice and methodology, hitherto invisible and mutually beneficial. *Four*, practice and terminology overlap in all the approaches, which might confuse elements of an investigation that should be separate, or that operate on a different level. An example relating to terminology would be "simulation" (see section 2). Webb's argument for conflating modeling and simulation [7] illustrates the problems that arise when different levels of practice are confused. She claims that because theoretical proofs require comparison to the natural world (in their evaluation) simulations should be seen as a class of model because they are *methodologically* similar. However, this argument conflates the levels (and processes) involved in relating natural to artificial. The evaluative processes involved in modeling and simulation may seem similar, but the scientific processes as a whole are different. We should not want to evaluate two different *processes* in the same way, even if they come up with the same answer, because we will have lost a distinction they started with: theory, empirical data and the natural world are different. For example, in modeling we are matching the *data* from the model with the known *data* about the natural system – this is because the natural system has been specifically and directly related to the model. In the evaluative stages of comparison, however, we are assessing and contrasting the artificial system itself with a natural system, or perhaps a concept. The relationship of each scientific process within each approach thus operates on distinct conceptual levels.

Following these level distinctions, the key epistemological difference lies in the way that comparative experiments can build or question theory, whereas models can represent or justify theory. Due to the character of their relationship with natural systems, comparative experiments and modeling have a number of distinct epistemological issues. We sum up the key philosophical questions in these approaches as:

- *Comparative* – how we can know something new from a process we cannot fully access; how knowledge is acquired when intuition is involved; how we simplify an experiment of a natural phenomenon which is a characteristic of many different kinds of species (e.g. learning); and how we might apply a re-conceptualisation of a theory into future scientific practice (see [2] for a discussion of many of these).
- *Modeling* – how models denote theory; whether models represent theories; how we build and simplify the natural phenomenon to create successful models (which as mentioned above is linked to producing evidence); and the processes of interpreting the models to form predictions [20].

The separation of epistemological concerns is important. If there are different routes to gaining knowledge there must also be different ways to question how we are gaining that knowledge.

Issues in the Confusion Between the Approaches. The engineering approach is more obviously distinct than modeling and comparison. However, despite the clearer difference it could still be confused with elements of the other approaches. We would identify two potential mistakes: a) evaluating the validity or usefulness of an artefact on the basis of how much it is bio-inspired; or b) drawing inspiration from a natural system to construct an artefact as an explanation of a phenomenon. For example, in the case of the termite-inspired building, it *would* be a mistake to evaluate the usefulness of this building because it is a faithful replication of a termite mound. The extent to which it is bio-inspired bears no relationship to the success of the engineered artefact. Its success is in lowering building and operational costs and increasing efficient air circulation – removing the need for air conditioning. So, although the termite inspired building is a good example of a *pro* approach, it would not be hard to see how it might be misinterpreted as either a model of temperature control or as a building that didn't look like a termite mound. An example of how this error manifests in artefacts that are constructed by faithfully copying a natural system – because they consider naturally-inspired design an accurate explanation of a phenomenon – can be found in the accidents (and fatalities) that occurred during the first human attempts of flight. Machines were built to imitate the structure and shape of bird wings because this was seen as an explanation of flight dynamics [27]. The first significant successes in flight were achieved only when the principle of imitation began to be separated from the design process.

An example that perhaps embodies both the issues with levels of explanation, and the confusion between using natural systems and aiming to explain them, is the potential for misunderstanding early (Classic) Artificial Intelligence. In Classic AI the metaphor of the *mind as computer* operated at a different explanatory level to the actual engineering and logic-based foundations, which focused on designing more useful computer programs [28]. Drawing on Cordeschi's example (in [10]), it would be a mistake to use the metaphor as more than a kind of explanation – i.e. as a basis to engineer an artefact to explain a phenomenon. A specific example of the distinct levels is found in the "frame-problem". This was originally an engineering issue for logic-based systems [28]; Dennet [29] subsequently noticed the epistemological concerns. The engineering problem has now been solved but the epistemological one remains an open debate [28]. If we apply the epistemological issue to engineering an artefact we would be holding the idea that a classic model of computer vision in a human environment could "see". Clearly, classical approaches to computer vision are models that work in experimental environments and the Classic-based-logic is sound; the issue here lies in treating the system like a natural one – as both an epistemic and *technological* artefact. Treating the artificial system like a natural one we have shown as characteristic of the epistemological comparative approach. Computational theories of mind thus operate at an epistemological level not an engineering one. Your laptop does not exhibit human behaviour *even if* some of its processing is akin to the processes of your cognitive system. The *mind as computer* is not invalidated as metaphorical use of a model, but it is invalidated as an actual hypothesis of human intelligence as a whole – there are no existing robots that exhibit human intelligence based on this Classic logic [30].

4 Conclusions

Distinction between comparative, modeling and engineering approaches can serve science and technology, resulting in clearer objectives and more effective interdisciplinary communication. As well as supporting dialogues within the approaches, our taxonomy would also aid cross-approach communication. ALife seems especially well placed for this [14]. We would however, like to point out that some overlaps between approaches *may* be fruitful [7]; one might even use artificial systems developed in a comparative framework as a basis for developing a model [4]. So, while we think that research must be classified clearly, we don't rule out the existence of additional approaches or advocate sharp distinctions that might hinder scientific or technological development. Application for future research includes the potential to develop new methodologies within the approaches. For example, the comparative approach could benefit from the practice of running experiments with natural and artificial systems in parallel, as outlined in [11]. Despite the greater issues faced in designing such an experiment (e.g. significant heterogeneity of natural and artificial systems) they might allow explanations of hypotheses without modeling. A further challenge would be explicating the relationship between artificial and natural in more complex cases, such as when a natural system is itself used as a model – sea slugs, cress and the common fruit fly are all now employed in science as (living) models of other systems. Finally, with the introduction of our *extended experiments* terminology under the comparative approach our aim is to cover a range of "actual" artificial systems acting as tools for conceptual thought: through this we hope to give "a new life to ALife".

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