A CRITIQUE OF AGENT-BASED SIMULATION IN ECOLOGY

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ABSTRACT

Models link empirical observations with formal reasoning. If the computer plays an essential role in their functioning, it seems only fair to consider theoretical computer science as well as the discipline of application. We review some perennial philosophical problems about the nature of state and behaviour in models from that perspective. A mathematical framework for their explication and the unbiased choice of solutions is proposed. Agent-based models play an increasing role in ecological modelling. They are taken here as an example for demonstrating critical assumptions and dilemmas in integrating criteria of methodological rigour with practical relevance of models. Some possible solutions and their practical implications are outlined based on this new theoretical perspective.

INTRODUCTION

Models link observations from the empirical realm with formal systems. From the technological viewpoint, we restrict the discussion to those models which can be implemented and executed on a computer. From the application viewpoint, we consider the field of ecology, representative for a wide range of "complex system" science disciplines: Ecology studies the relationship between organisms and their environment. Development, application and testing of ecological models requires a correspondence to some selected empirical or theoretical aspects of these phenomena.

In ecology the empirical realm is characterized by data about the configuration and the behaviour of organisms, populations, or ecosystems. Organisms are the key notion of life sciences. Here we will focus predominantly on time series documenting the environmental relationships of organisms, i.e. their behaviour. Many key aspects of life are easily and naturally expressed as behaviour: living, surviving, reproducing, growing, etc.

The theoretical realm employs mathematics, i.e. axioms, theorems, and logic. The relationship between the empirical and the mathematical is not universal, but depends on context and observer perspective. In other words, models inevitably have a perspective, they are models of or for somebody, e.g. the meaning of their language is embedded into human cultures. At the same time computer models can be regarded as mathematical machines.

In ecology and other environmental sciences, it often seems that models can either be methodologically rigorous or practically relevant but rarely both (Peters, 1991). We shall refer to this situation as the *modeller's dilemma*. The puzzle why this is so can be posed in the form of four steps:

Theory in Ecology

Compared to other natural sciences ecological theory is relatively weak. Over the past years modelling has almost completely taken over from theory as a topic at ecological conferences. Some ecologists have even expressed their opinion that there can be no theory in ecology because systems which ecologists are dealing with are too complex and too poorly experimentally conditioned. The pragmatic interest of funding agencies have pushed modellers towards the empirical side.

Agent-Based Models in Ecology

The increasing importance of modelling and simulation in ecology is best exemplified by the ongoing proliferation of multi-agent models. This change is driven by technical progress in soft- and hardware rather than theory. In ecology these models have become known as "individual-based models" whereas in social sciences the term "agent-based models" is favoured. The two terms will be used synonymously and abbreviated as ABM.

Theoretical concepts behind Agent Based Models

ABMs as other simulation models run on mathematical machines. Thus there must be implicit and inevitable assumptions about abstractions and interpretation of ecosystems built into these ecological models. Even if a modeller were convinced that ecosystems and ecology in general cannot have a theory, the mathematical machines they are using for analysing their data and for expressing ecological concepts have theories beneath their user interfaces. The pragmatic turn to applied research has only resulted in their hiding. Here we want to show that consultation of theoretical computing sci-

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ence will make some of these implicit assumptions behind models more explicit and transparent.

Mathematics of Agent Based Models

Physics has been the main and almost sole provider of scientific modelling prototypes, concepts, and paradigms. From the 19th century onwards these paradigms have been implicated in the formation and world views of other disciplines such as ecology, economy, or anthropology. Today computer science has emerged as a contestant in the field of modelling (especially interactive) behaviour. In this respect physical models have been weak, since they disregard the notions of choice and memory, i.e. subjective nondeterminism and dependence on history, that are so prominent in phenomena studied by life sciences. Physics has been named the science of simple systems, but whether or not a system is indeed simple, and in which respect, may lie in the eye of the modeller.

Theoretical computer science has studied formal behaviour (automata, process calculi) for a long time, and has recently come up with a unifying approach of formalizing behaviour of systems (Rutten, 2000). Since modeller's in ecology and especially users of ABMs often adopt a pragmatic perspective, they may overlook a mismatch between the physical modelling paradigms they are using conceptually and the computational tools they are employing technically. The following essay starts from the suspicion that a fundamental inconsistency may lay between *how* and *for what* ABMs are used in ecology, and potentially in social sciences as well.

We will use results of the new formal approach from computer science to discuss the implications for the interpretation of simulation models in ecology. They allow a new perspective at the modeller's dilemma in ecology, and ABMs in particular may take a key role in promoting this "interactive turn" in ecological modelling. The most important change is that these models allow for the formal representation of additional *empirical content*: i.e. interactive features in the behaviour of Life can formally be accounted for, whereas physical models inevitably abstract from such aspects. It is a separate question whether or nor living systems contain these features. Interactive models are expressive enough to allow testing of these hypotheses.

TERMS, DEFINITIONS

We use behaviour, as it is displayed at interfaces between organisms and ecosystems and their environments, as the prototype of an ecological data set. This type is exemplified by gas and energy exchange of plants or vegetation canopies, growth of biomass or changes in population size. Time series is the typical data format, especially with fairly static spatial coordinates, e.g. behaviour of plants.

Empirical Aspects

How can temporally ordered observations be expressed in mathematical language? From an empirical point of view the criterion is how to keep the key intuitions about living systems, while abstracting from the contingent details. Which attributes of a time series can be abstracted from, and on which one should the formalisation focus? One extreme attitude in this respect is simply to keep all attributes of a data set. This has been termed "petabyte science" and is the ultimate stance in data-driven research: "Petabytes allow us to say: 'Correlation is enough.' We can stop looking for models. We can analyse the data without hypotheses about what it might show. We can throw the numbers into the biggest computing clusters the world has ever seen and let statistical algorithms find patterns where science cannot." (Anderson, 2008) The following quote illustrates this pragmatic attitude further: "This is a world where massive amounts of data and applied mathematics replace every other tool that might be brought to bear. Out with every theory of human behaviour, from linguistics to sociology. Forget taxonomy, ontology, and psychology. Who knows why people do what they do? The point is they do it, and we can track and measure it with unprecedented fidelity. With enough data, the numbers speak for themselves." (Anderson, 2008)

Obviously, such approaches invoke applied rather than theoretical computer science, and constitute business plans rather than science. Even if the resulting description may again be termed models, they encode phenomenological and operational facts rather than hypothetical explanations. On the other hand, the same data can be treated with exact and logical methods without sacrificing the behavioural focus. From a theoretical perspective this approach turns away from explanation and prediction of states to classification and evaluation of behaviour.

In order to clarify the conceptual issues involved we need the notion of *streams*. A stream is a sequence of symbols from a finite alphabet where each symbol depicts an event at an interface. Attributes of streams are extensionally defined as the set of all streams which contain a respective property. Compiling all streams implies then capturing all attributes observed. However, the classification of behaviour into meaningful subsets and the assignment of appropriate and correlated labels remains a major task within this approach. Closely related is the theoretical question whether these sets of classes also have an *intensional* description as a formula. Such descriptions summarize the attributes in abstract notions of a mathematical language. Hence this results in the question which formal language is *expressive* enough for keeping the key intuitions about living systems? Which of these expressions are appropriate with respect to the empirical content?

Theoretical Aspects

In addition to the progress in computing power and storage capacities there is the theoretical side of computer science. The concepts formalising behaviour are phrased in terms of logical calculi. From this perspective one asks the perennial question of formal logics, namely whether valid formulas can be derived from an axiomatic system? Here *completeness* and *correctness* are the interesting properties: is there an axiomatic basis allowing for the deduction of all and only true/valid formulas, respectively?

Rosen (1991) proposed using *category* theory to formalise the modelling approach in biology and to specify how modelling relations of organisms differ from physical objects. This early introduction of categorial methods into life sciences provides the backdrop against which recent theoretical breakthroughs in computer science can be discussed below.

ONTIC AND EPISTEMIC STATES

We summarise the theoretical results in a non-formal manner. Two terms are used as the point of contact between empirical data and theoretical reasoning: *ontic* and *epistemic* states.

They stand behind one of the oldest and most important distinctions in western philosophy: between the world as it *is* and how it acts upon its observers, i.e. how a world *appears* to us or to other organisms. This distinction has been very useful for the systematic study of nature in a number of disciplines. In physics it has clarified the role of measurement and in mathematics the role of axioms and logic. Though none of these topics has been settled yet, the ability of distinguishing ontic from epistemic aspects is deeply implicated in the progress these disciplines took since the late 19th century. In ecology, however, this distinction has no prominent role today. Ecologist are typically pragmatically oriented, searching for empirical evidence in the form of field data and have little theory at the disposition to count on. Here we argue that the widespread neglect of the ontic–epistemic distinction can have severe consequences when judging models and the potential of new modelling techniques in ecology. We will take the implications of agent based models as an example how to represent, explain or evaluate behaviour of living systems.

Modern technology provides many examples of the difference between the way artefacts make their behavioural appearance in the world and their true internal state. Epistemically we perceive e.g. a red light on such machines when they display undesired behaviour, e.g. low battery, no coffee, or other malfunctions. Of course, the corresponding error states to this behaviour such as the red light are epistemic states and not the cause for the dysfunction. It rather signals an appropriate action to be taken by us, which in most cases does not involve at all the search for the true causal state of the problem. Neither does it help to distinguish proximate and ultimate causes. The degree to which we can ignore the causal states during the usage of these artefacts can be taken as a measure of a “ripeness” or robustness of technology. Computer science serves as the prime example here: It has become a design principle to impregnate a specified program behaviour against the various software and hardware options by which it can be implemented, often advertised as “compatibility”. The behaviour of software is specified in a way which makes it general and abstracts from the details of implementations. This robustness is an explicit goal in human software design, and hence an ontic feature. It might be suspected that similar principles can be found behind the robustness of biological and ecological behaviour. As a sceptical scientist, one should then ask whether robustness of Life is ontic or epistemic.

The important point for the following discussion is distinguishing between the choice of access to a phenomenal realm and the choice of models which handle the transition between ontic and epistemic aspects, and the disappearance of the respective distinctions.

Historical Example: The Invention of Perspective

We start with a motivating example, albeit from a very different field: The historical change in the perception of space can be phrased in the ontic–epistemic distinction with respect to system states. From late antiquity up to the Gothic epoch there was no concept of space in the modern sense. Space without objects could only be talked about as emptiness, it had no properties. There was no abstract embedding of the painting of a scene as projecting from three to two dimensional patterns. Gothic painters had to focus on the ontic aspects, how people really are (and seen by God). People were placed into pictures due to the real size or due to their real importance and not how they appeared to us, due to their distance from the viewer. By contrast Renaissance painters used the epistemic states instead and mastered perspective as a technique of representation. They could distinguish between the real person and the model of it in the form of a painting.

They had a language in which the subjective (epistemic) impression of the observer of a scene could be handled objectively. This made the original (the real thing) and the impression in the eye of the observer congruent. The original could be replaced by the painting and the impression (from that point) would not change (see the instructions by Dürer how to do this). In other words they had a modelling language and praxis in which the change from ontic to epistemic could be controlled, while some aspects of the empirical realm remained invariant. This is also a fair description of modelling in physics: physical theory today is also a theory of the measurement process. This allows separation of concerns and a controlled transition between the two perspectives.

Actual Example: Simulators

The success of chess computers serves as a second example phrased in the ontic–epistemic distinction, but now with respect to system behaviour: These machines do not possess a winning strategy yet, but their performance has been boosted to world-champion level by improved evaluation abilities. Even for today's computer a typical prediction task from a midgame situation is unsolvable in general due to time constraints. That is why the ontic state, that is, the configuration of pieces on the chess board, cannot be linked effectively to the behavioral problems of interest: Who will be the winner? What is the final configuration of the game?

The epistemic state that both human and machine players act on consists of certain patterns of configuration that have been heuristically established. The machine representation of "behaviour space" is derived from already played games, preferably those between expert players. That is why modern chess computers can be regarded as local *representation* of the cultural memory in chess, while they remain unable to construct this memory autonomously from scratch.

The third example is checkers, where a winning strategy has indeed been discovered and implemented. The complete decision tree of this game has been annotated with corresponding potential final game configurations. In this case the configuration of checker pieces on the board is the effective ontic state, the behaviour can be reduced to a deterministic *function*. If white opens and plays a winning strategy the result is given. Black may remain ignorant about the fact the he will loose for most part of the game. In this case the choices made and human hopes experienced during such a game represent epistemic states only.

The above examples showed on the one hand the invention of a language expressive enough to characterize the distinction between epistemic and ontic states (typically by reflecting on the observation process and its limits). On the other hand the introduction of adequate models and formulas allows a smooth transition between them, ultimately obliterating the distinction: results from the formal derivation by (correct) model logic are the same as results from observations (phrased in an expressive language). In the perspective example this problem was posed for paintings: modelling of this process is successful when objects in represented abstract space appear indistinguishable from real space. In the gaming example the same problem was posed for choices: modelling of this process is successful when virtual choices and behaviour in represented (game) time appear indistinguishable from actual games (in real time). Note that in the first example temporal changes in objects are not important and can be abstracted from, while in the second example the inner state of players behind a game interface can be abstracted from.

Now we can turn to ecology and look there for corresponding cases. The key questions are: Firstly what attributes of the (empirical) world do we want to express in sufficiently expressive mathematical language?

- A behavioural, possible not locally decidable aspect, such as the ability to win a game, to master a situation in a simulator, the ability to have fertile offspring, or
- a configuration aspect, with possibly unforeseeable global consequences that appear as emergent behaviour, such as the reconstruction of local structure from simple building blocks.

Which of these aspects is more important in capturing intuitions about Life? There is no doubt that the mathematical tools will be different. And secondly how can we put the formulas (theorems) expressed in this language into a logical context? How do these theorems relate to formal deduction? Is there an axiomatic basis allowing to derive these formal expression as valid, in other words is there a theory available for a given realm? The advantage of category theory is that the theoretical possible answers to these questions can be derived within one framework and thus allowing to postpone the interpretation until after a modelling or simulation exercise. We will show below that current agent-based models, not only in ecology, come often hard-wired with an (extreme) implicit decision on these matters: ontic and epistemic descriptions are constructed as equivalent. In the remainder of this article, we shall argue that this decision is theoretically unnecessary, and empirically dubious.

Applied to Ecological Data

The behaviour of an organism is what is seen or experienced by human observers. Organisms cannot (yet?) be constructed from building blocks; they need to be taken out of one single (unique) context of natural history. That is why their behavioural aspects naturally dominate characterisations in ecology. Hence states of ecological systems come in the form of epistemic states. Corresponding ontic states (if they exist) need to be inferred (through a modelling exercise). Here we allow for the explicit possibility that organismic behaviour may include non-local attributes: for instance, the ability to eventually have fertile offspring is regarded as an adequate criterion for fitness.

In engineering problems, that is, in the design of system behaviour, similar non-local properties occur. They are often even necessary to rule out trivial, unproductive solutions; for instance, a computer program that guarantees never to answer incorrectly by simply not terminating, or a traffic light that prevents accidents by giving way to no one, or the prolonging of one's own lifespan by cryotechnology.

In theoretical computer science these features have been termed *liveness* properties. We suggest that the term carries more than metaphorical resemblance to its biological original, and that its mathematical explication can be re-imported backwards into theory of living systems. In physical models these properties are not needed and typical models are designed to exclude them. In the modelling approaches discussed below, however, these possibilities are considered. Only in this more expressive language one is no longer forced to abstract from them before a quantitative modelling exercise is even started.

The typical definition of non-local properties in time series is extensional (the set of streams in which it occurs). The corresponding intensional abstract formulation can be provided by *modal/temporal logic*. From a theoretical viewpoint the empirically testable question is then whether or not liveness properties will turn out as helpful when coding the empirically intuitive aspects of living systems into simulation models. In order to test this, we select a mathematical approach which is unbiased in dealing with non-local properties.

The terminology introduced above allows a separation of the two following concerns:

Empirical grounding of models in local versus non-local features. This leaves open the decision whether or not non-local features such as liveness really exist in the world of living organisms; note that liveness is a technical term in computer science, while living organisms is a key concept in ecology.

Theoretical treatment of behaviour as a derived or fundamental feature (constructed by equational versus represented by modal logic, respectively). This leaves open the decision whether or not modal logic is indispensable in ecological theory, it leaves open the related question whether ecological systems may have a concise theoretical representation (in behaviour space) or whether this is impossible because their configuration is/appears as “too complex”.

The first concern is addressed by decisions about the formal language for abstracting from data sets. The second concern is addressed by decisions about the formal tools for relating behavioural and configurational aspects in the model. This decision may reverse the relationship between fundamental and derived. In most physical models behaviour is reduced (simplified) to deterministic functions of changes in (ontic) states of the system. Here the characterisation of states is fundamental and the changes over time derived. In models of interactive games the fundamental role is taken by the space of possible behaviour while the (epistemic) states are reduced (simplified) to mere indicators of behavioural choices/classes at an interface. In current ABMs, as will be shown by a typical example from ecology, these details of the ontic–epistemic distinction are not left to the user, but already fixed tacitly by the software package.

EXAMPLE OF AN AGENT-BASED MODEL FROM ECOLOGY

The following case study describes a reinterpretation of an ecological model by Jovani and Grimm (2008), implemented on the popular ABM platform NetLogo (Wilensky, 1999). The model intends to explain the synchronicity of breeding behaviour in a bird colony in terms of the behaviour of individual birds. In its explanatory goal, as well as its numerical algorithm, the model resembles models in physics. The chosen model is regarded as a typical and pedagogical application of an ABM in ecology.[1] Our critique is aimedd at the mathematical structure of the model, which could be implemented in any ABM framework, not at the particular features of NetLogo. These models have become popular tools in social and life sciences mainly based on their pragmatic success in case studies. They allow the automated generation of global structural and behavioural patterns in a bottom-up manner, e.g. in self-organising systems from simple building blocks and their local interactions Gilbert (2008). Potentially they are powerful tools for generalising beyond case studies Grimm and Railsbeck (2005); Hauhs and Lange (2006).

As typical in ecology the case study starts with a characterisation of organismic behaviour. In a breeding colony birds show a wide range of interactive behaviour; they compete for space, defend nesting sites, attack neighbours, steal nesting material, fight and wound each other; but ultimately and almost miraculously they settle down calmly and begin breeding. In many environmental situations the synchrony in breeding is related to the overall reproduction success of a colony. Hence it is of interest for ecologists to understand the initiation and spread of behaviour which leads to synchrony. The goal of the ABM by Jovani and Grimm (2008) is reproducing and explaining the spatial breeding patterns in a bird colony from local interactions among neighbours.

Translated into an ABM

Characteristic features of the bird colony are translated into and simulated as an ABM. The *behaviour* of the neighbours of breeding birds is regarded as critical for the success of reproduction. The term *arousal* can be interpreted as an indicator whether a neighbour bird might for example tend to display aggressive or appeasing behaviour. Behaviour towards neighbour birds is the key observation (also for birds) to classify the “arousal state”. Note that this classification of arousal as epistemic states for field ecologists, does not change with scale, or with proximate and ultimate “explanations”. Even if field ecologists had mapped the DNA of successful and non-successfully reproducing birds from the colony that correlate with arousal these DNA states would still be epistemic states. Thus in the description of the ecological problem leading up to the design of an ABM it is clearly treated as an *epistemic* state identified by the corresponding behaviour.

In the subsequent modeling section of the article by

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[1] We have used the code of the original model in student courses. It is used in a recent textbook on Individual Based Models Grimm and Railsback (2011) as one of the introductory examples into this modelling technique. It also appears as design on the associated web page.

Jovani and Grimm (2008) arousal becomes one of two *causal* state variables which characterise a bird in the ABM. The transition takes place in the sentence on page 2 when the authors state their hypothesis about a potential mechanism explaining synchronous behaviour: "If egg laying depends on . . . " What could have continued as dealing with a classification of adaptive behaviour becomes from this point on a problem of searching for an explanatory mechanism of changes in an ontic state variable.

Within the subsequent sections on the ABM the arousal state is used as a typical causal (ontic) state from dynamical theory. Its use falls under the typical physical approach to modelling. The documentation scheme ODD (Overview, Design concepts and Details) for ABMs does not include nor require criteria which would allow distinguishing between causal (ontic) or epistemic states Grimm et al. (2006); Grimm and Railsback (2011). ODD intends to make the theoretical assumptions clearer such that the model is easier to reproduce Grimm and Railsback (2011). It does so by imposing a translation scheme into a dynamical system which closely matches physical models. This reflects the way in which many ecologists think about their system and the way in which most computer programs are developed in ecology. However, it restricts the running ABM computer codes to only one of the two possible interpretations, see below. This pre-selected abstraction and implicit model choice may even be the less-suited one as it is argued here the case of the breeding birds.

The article by Jovani and Grimm (2008) deals with epistemic states throughout the introduction. Then, in the section specifying the ABM only causal states are used, and with the first sentence of the discussion the reader is taken back to the perspective of epistemic states, when the relevance for synchronicity in breeding is discussed as adaptive behaviour or not.

Jovani and Grimm (2008) propose a number of field observations which can be predicted from their model. None of these takes the model out of the range of observations discussed in the introduction. It can be argued that the ABM can serve as a valuable tool for testing the consistency among different field observations. In this sense ABMs can be used as pragmatic communication tool about case studies; seemingly without much theoretical overhead. For physical models proper, by contrast, only predictions beyond the range of previous observations, so-called *nontrivial* predictions, count as a full validation.

DISCUSSION

Terminology such as "mechanism", "prediction" or "explanation" in the introduction and discussion of their paper is by no means unique for Jovani and Grimm. It reflects the general use of these terms in ecology, in particular in not distinguishing the two types of prediction. One advantage of the ABM is thus that it makes this terminology amenable to formalisation and critique by offering an alternate interpretation. There are several possibilities of deriving categorial formalisation of the breeding colony. Three of them will be presented and discussed informally.

Formalised as Bialgebra

A bialgebra is a mathematical form of models in which the complete possible behaviour is distributed stepwise over local (ontic, causal) states. A bialgebra implies two parallel decisions in the choices posed at the end of the preceding section: Behaviour cannot extend beyond deterministic functions (restricting observations to local properties) and is dependent on state changes (ontic states as fundamental to the dynamics). It has been shown that the mathematical structures underlying the ABM by Jovani and Grimm (2008) and many other typical and pedagogical examples, namely multidimensional cellular automata, can indeed be phrased as bialgebras (Trancón y Widemann and Hauhs, 2011). The analysis is mainly on the level of semantics, but for simple models such as the one of Jovani and Grimm (2008), the bialgebraic form directly yields a feasible algorithm for reimplementation and reproduction of results.

Such an approach implements the strongest possible assumptions about relationships between states and behaviour in the modelled realm. In a bialgebra epistemic states are set as congruent with ontic states and the complete behaviour can be set in a one-to-one mapping from these states. Thus behaviour can be predicted from the states, and these can be uniquely identified by observable behaviour in turn; the model is *fully abstract* in the jargon of theoretical computer science. Such models represent a maximal combination of constraints: behaviour has only locally observable attributes and system states can be constructed from attributes of building blocks. Philosophically this represent a modern form of Laplace's Demon or an "anti-holistic" modelling universe. Emergence in the sense of aggregate behaviour that is not *logically* determined by constituent behaviour is excluded in such a universe.

This new theoretical approach has the advantage that it separates the theoretical concerns and allows a second alternate (behavioural) interpretation in the ecological realm. In a categorial framework the decisions on interpretation and modelling paradigms can be separated from and made independently, even after the modelling! This is only possible because the change of perspective affects only the meta-level language of discussions about the model, but not the logics within the model, since by virtue of the bialgebraic structure, behaviour and states are fully equivalent in such a "reductionist's paradise".

The caveat of using a bialgebra is that it combines two drastic abstractions: In physical (functional) models one abstracts from non-local behaviour reducing any observed change to a deterministic function while retaining an advanced powerful concept of causal observable states. In interactive (game) models one abstracts from causal (effective) states, while retaining an advanced powerful concept of non-local behavioural attributes (such as fairness, liveness, etc.). The two modelling approaches are categorical duals of each other (Hauhs and Trancón y Widemann, 2010), with their own respective testing criteria and blind spots. In the bialgebra approach, however, the two strong simplifying assumptions are made at the same time, by treating epistemic states as causal and interactive behaviour as functional. This puts a heavy load on the user arguing in favour of its plausibility. In addition it leaves this type of ABMs stranded between difficulties of testing against empirical data and difficult theoretical justifications.

Formalised as Course-of-Value Recursion

The next step towards a more powerful and expressive conceptual basis is dropping the identity of epistemic and ontic states on which the bialgebra was based. Instead of using the full-blown notion of ontic states with their implied causal power, only epistemic states are used, which are more readily supported by empirical data. Documented behaviour must be extended over time, that is why a more advanced instrument is needed than in the previous example for dealing with history. In a bialgebra one temporal slice of the system's state fixes future behaviour. Here epistemic states need to be recursively defined through past behaviour. This is not accommodated by the type of recursive relationship underlying state transitions in dynamical systems, which deal with instants only. A suitably generalized form of recursion has been formalized in the category-theoretic framework (Uustalu and Vene, 1999).

The resulting "historic space" is highly redundant, but models can be understood to operate on virtual states represented as equivalence classes of histories with undistinguishable future behaviour (Trancón y Widemann, 2012). The resulting models will resemble physical models and will still be able to construct trajectories. They could still seek explanation in the sense of traditional ABMs, but the assumption about accessible ontic states or the implicit identity between ontic and epistemic states is dropped. Hence models could allow a much more careful interpretation of observations, while keeping the (reductionist's) optimism about theory and explanations and predictions.

Formalised as Coalgebra

The fullest application of an alternate approach would use coalgebras as the fundamental level in an ABM. The coalgebraic approach subsumes a variety of high-level system models such as automata, graphs and networks, and behavioral differential equations (Jacobs and Rutten, 1997; Rutten, 2000), but is not recognized theoretically outside core computer science. Hence there is no real-world ecological example available today. Only a simple application to the logistic map following an idea due to Rutten (2000) has been made (Hauhs and Trancón y Widemann, 2010). The goal is to keep the model firmly in the behavioural perspective, while using only epistemic states as indicators of the undistinguishable classes in behaviour. At the same time a corresponding temporal logic could be applied and tested for the occurrance of non-local properties in the empirical data base. It is known that modal and temporal logic relate to coalgebraic models and theories in the same natural way as equations do to the algebraic models of physics (Cîrstea et al., 2008).

The "agents" in such a ABM could no longer be used in order to explain a phenomenon, but only to assess and evaluate the accumulated observations. Confer the famous "dining philosophers", a completely non-causal but nevertheless extremely illuminating model of resource contention. Applications of such models in ecology would resemble more the use of a flight simulator as a tool facilitating the communication within an expert group, rather than the use of non-trivially predictive simulators such as behind weather reports. A "flight simulator for foresters" in form of an interactive growth simulator of managed forests is another example of the former approach (Hauhs et al., 2003). In contrast to the case study discussed above, coalgebraic ABMs will clearly delineate the task of *evalulating* a given behaviour in given environment as adaptive, from the task of explaining or *predicting* this behaviour from observable states.

CONCLUSION

Here it is suggested that users of ABMs start looking at the mathematical structures beneath the friendly and versatile interfaces of their programs. This friendliness, as in the case study above, may come with a heavy philosophical load, of which many user may not be aware. With the help of theoretical computer science these structures can be unravelled and reversed, the implicit assumptions relaxed and other views at living systems may be opened for quantitative and formal assessment. There is a parallel move on the side of theoretical computer science where new formal tools for expressing behaviour and formalising choices are ready and searching for application in new fields. ABMs have the potential serving the role as an exchange between the empirical side of "complex system sciences" and the theoretical side of computer science. In order to develop this niche further, however, some of the now implicit assumptions in these models have to be lifted to the surface and put under control of their users.

The new approach provides a new perspective at typical problems in ecology: Models are not capable of providing non-trivial predictions. They need to be calibrated and are often more a concise summary of patterns in large, multidimensional datasets rather than an explanation of what goes on in an ecosystem. From the perspective of the categorial framework it is no longer necessary that these features are taken as characteristic of the ecosystem itself, e.g. because it must be supposed that living systems are inevitably complex ones. There is a second reading of these modelling problems, they may directly result from inappropriate modelling approaches. To begin with, becoming more aware of these issues ecological modellers need to reflect on the ontic epistemic distinction when introducing state variables.

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