Theories of Complexity

Common Denominators of Complex Systems

Complexity scientists often express the need for the development of a theory of complexity. One of the major problems on the way toward such a theory is the lack of a generally agreed on definition of complexity. In this article it is proposed that, whatever definition one might one day agree on, contextuality and radical openness are essential features of complexity. Both properties are clarified by means of an example and implications for a future theory of complexity are discussed.

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INTRODUCTION

During the last two decades or so, a new field of interdisciplinary research, often referred to as the "science of complexity," emerged from the interplay of physics, mathematics, biology, economy, engineering, and computer science. Its mission is to overcome the simplifications and idealizations that have lead to unrealistic models in these sciences (the "spherical cows" as Bak [1] coins it). One of the most important methods of the science of complexity is the use of a particular kind of computational model, so-called agent-based models (ABM) [2,3]. Examples include rather abstract models such as Holland's ECHO [4–7]), artificial stock markets [8], simulations of social systems such as *Sugarscape* [9], realistic models of social insects [10,11] or accurate implementations of real road traffic systems such as Transims[12] to name but a few. These and other empirical successes have served as motivation for reflection and debate on the possibilities of developing a body of scientific *theory* in the extension of these new lines of research. The theoretical issues are, however, far from being resolved. For instance, there is still no generally accepted definition of complexity, despite a vast number of proposed *ansatzes* [13,14]. This article aims at contributing to the further development of the theoretical foundation of the science of complexity by addressing the much-discussed issue of the possible future formulation of a unified theory of complexity and/or complex systems (from now on: a TOC). Several authors (particularly Holland [4,15], but also see Casti [16], Fontana and Ballati [17]) have expressed the feeling that such a TOC would be necessary in order to make the science of complexity more coherent, general and precise; indeed, the search for universal and unifying theories is something of an ideal in most scientific disciplines.

There have been several attempts to formulate general principles which guide the behavior of complex systems. Among these, the most prominent attempt is probably Per Bak's "self-organized criticality" (SOC) [1,18–20], which was proposed as a theoretical framework to explain peculiar features of a range of natural systems ranging from earthquakes, via forest fires to extinction and speciation events during biological evolution. As such it has contributed substantially to the theoretical debate, but the idea of SOC as a universal source of complexity has been repeatedly criticized [21,22] and can now be regarded as essentially rejected.

A currently well-regarded candidate for a unifying notion of complexity is that of complex adaptive systems (CAS). John Holland observes that many intuitively complex systems share deep commonalities although they seem very different from each other to a superficial observer; examples of such systems are national economies, stock markets, immune systems or social systems.

> Among those who have carefully compared different CAS, there is little doubt that they form a coherent subject matter. At the right level of abstraction, their mechanisms and processes can be given a unified description. Within this framework we begin to see common causes for common characteristics. . . . The challenge is now to provide a rigorous treatment of these observations. [5, p. 332]

The challenge pointed out by Holland in 1994 is still open, which is not surprising, considering the young age of the new science of complexity. There is also considerable doubt whether the task is at all feasible, or if complex systems rather are too diverse to share any *profound* "common causes for common characteristics." External critics of the "science of complexity" (such as Horgan [23] or Sardar and Ravetz [24]) seem to hold this view. Although the early successes of complexity research have indeed invoked a widespread belief into the viability of a TOC, today many prominent proponents of the science of complexity (as for example, May [25]) seem to have reduced their expectations and also doubt the absolute need of a TOC. Their point of view seems to be that the science of complexity can still be productive even if it does not possess a rigorous overarching theory. On the other hand, the concepts of and insights from the study of complex adaptive systems are currently being imported into various scientific fields as a theoretical foundation for the understanding of complexity within these respective fields, including medicine [26,27], economics, organization psychology [28], and others, displacing ever more "spherical cows." In this literature, CAS frequently appears synonymous with complexity.

There is no unique, simple criterion or litmus test to decide if a theory is scientific or not; scientific activity across the range from botany to particle physics and epidemiology is too diverse.

Thus, both with regard to the internal theoretical foundation of the science of complexity and its external use in neighboring sciences, it is important to assess to what extent CAS can serve as a general approach to complexity. This question is in part scientific and in part philosophical, and it has various precursors in the literature [29,30]. We have found it useful to discuss the question in the context of the existing debate on the possibility of a TOC, by trying to clarify what exactly a TOC could and should offer and what specific form it could take. We shall discuss the possible contents and scope of a TOC, especially what kind of phenomena and systems it can be applied to, but also the nature of the relationship between the theory and the systems it would be supposed to account for. Of crucial importance in this respect is an adequate understanding of the intrinsic difficulties with representing complexity in computer models. In section 2, we will draw on contemporary philosophy of science to clarify somewhat the notion of a scientific theory. In section 3, we shall present our main example of intuitively recognizable complexity, that of the introduction of Nile perch into Lake Victoria, which will illustrate some of the challenges involved in the modeling of that complexity. In section 4, we introduce the concepts of "radical openness" and "contextuality" to further analyze the case of Lake Victoria. It will be argued that there are generators of complexity in the real world that in some cases impair the possibility a well-defined and workable distinction between system and ambiance. To the extent these generators of complexity are of practical relevance—and we think they are—there are aspects of complexity that cannot be accounted for in terms of complex *systems* in the normal sense. Thus, a general and unifying TOC cannot restrict itself only to a treatment of complex systems, and conversely, a theory of complex systems will be to "simple" to exhaust the universe of complex phenomena (section 5). However, it seems unlikely that one can predict or control phenomena that evade description in terms of a well-defined system, and this may limit the utility of a TOC. Ultimately (section 6) we shall therefore analyze the possible use of a TOC, concluding that we need knowledge of simple and complex systems as well as deeper layers of complexity such as radical openness and contextuality, the exact choice of the focal point being above all a pragmatic and case-specific issue.

SCIENTIFIC THEORIES AND TOC

Along the lines of the current debates on the possibility of a TOC, we shall assume that the TOC will be a *scientific* theory. By this choice we do not disregard the value of the 2500 years of philosophical thinking about this question (from Heraclite and Lucretius to present thinkers such as Cilliers [31]). They just fall outside the scope of this article. We should ask, however, what exactly it involves for a theory to be scientific. Philosophy of science studied this question throughout the 20th century and basically concluded with the absence of a straight answer. There is no unique, simple criterion or litmus test to decide if a theory is scientific or not; scientific activity across the range from botany to particle physics and epidemiology is too diverse [32,33]. Thus, rather than looking for universal criteria for being scientific, it is often better to ground criteria in the *aim* of the theory [34]. Three aims are central:

- Prediction of the future behavior of a system given a set of observational data about it (predictive component).
- Theoretical understanding and/or description of a system (explanatory component).
- Provision of guidelines and control mechanisms for the intervention and manipulation of systems (control component).

Ideally, a scientific theory would explain, predict and facilitate control at the same time. The best examples of such theories can be found in physics. Quantum mechanics, for example, not only provides an explanatory framework for a number of phenomena such as emission spectra of elements, atomic and molecular bonding, superconductivity and many more, but also allows an accurate quantitative prediction and experimental manipulation of those phenomena; furthermore quantum mechanical systems can be manipulated in such a way as to allow their exploitation for the construction of technology. Control, prediction and explanation go together in quantum theory. This is not the case with all scientific theories. Evolutionary theory, for example, lays most emphasis on the explanatory component whereas prediction and control are negligible factors.

A central and related issue is the language in which a TOC is to be formulated. Science is largely dominated by a Platonist ideal [35]. The essence of this ideal was established in mechanics by Galileo and its most important success is maybe theoretical physics. Often, a TOC is (more or less tacitly) assumed to be a mathematical theory [4,15,36]; Holland, for example, points out that the mathematical form has the additional advantage of high precision and generalizability. One could add that prospects of prediction and control might look better if a mathematical form is possible. Indeed, quantum theory is wholly formalized and quantitative. In contrast, the theory of biological evolution by means of natural selection, for example, involves mathematics only for the formulations of details, whereas the main insight is formulated in natural language. A TOC might be of this latter kind.

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Another element that is tightly woven into a Platonist/Galileian paradigm is the idea that natural systems can be separated into a relatively simple essence plus irrelevant perturbation or “friction.” The latter acts like a curtain to hide the basic principles of nature’s working. It is the craftsmanship of a good scientist and modeler to be able to separate those components and to see the simple principles that guide natural phenomena. We will see in section 3 that this aspect of the Platonist/Galilean paradigm is intrinsic to all formal modeling methods. This will be relevant insofar as we will find it at odds with certain characteristics of some natural systems.

Let us now turn to another important property a TOC must have: Universality—a TOC should be applicable to, if not all, so at least to a wide range of different complex natural systems. There do exist theories of complexity in various fields like for example computer science [37,38] or mathematics [39]. Those theories are based on very precise, but also narrow, notions of complexity; in consequence they fail to provide insight into a broad spectrum of complex systems and therefore disqualify as candidates for a universal TOC. In a Platonist/Galieleian science tradition the idea of universal theories is often equated with unified theories. A unified TOC would encompass models or theories of prior attempts to study particular complex systems (compare Holland [40]). Note however that, although unification is of high aesthetic value, it should not be regarded as the only possibility for a universal TOC.

We conclude that as a minimum requirement, we would expect a TOC to be useful in controlling natural systems, or to be predictive, or to be explanatory. It should make some claim of universality; however, unless new Platonist revelations are on the way, one would expect a possible trade-off between universality and mathematical quantitativeness.

COMPLEXITY AT LAKE VICTORIA

In the previous section we have tried to clarify some formal aspects of a TOC. In this and the next section we will discuss some minimal requirements on the contents of a TOC. In what follows, we will discuss an example of an intuitively complex system and try to extract from it the properties that seem to be important for its complexity. Our strategy will be as follows: First, we will identify generators of complexity in the specific example-system; second, assuming that the system falls within the scope of a TOC, we will conclude that a general understanding of complexity must somehow take those generators into account. Finally, we will look at the implications of these properties of complexity upon the general form and contents of a TOC.

The example we have chosen is the, among ecologists, rather well known case of the introduction of an alien predator species—the Nile perch—into Lake Victoria, the second largest freshwater lake in the world (our account of the events is largely based on Goldschmidt [41]). Prior to the introduction of the Nile perch there were more than 300 different species of cichlid fish in Lake Victoria, mainly of the genus *Haplochromis.* These species were genetically very closely related to one another, but nevertheless they represented a broad spectrum of different survival strategies. It appears that they quite recently (possibly not more than 15,000 years ago) began to fan out into different ecological niches with different food sources such as insect-larvae, detritus, scales of other cichlid fish, and many more. Before the introduction of the Nile perch, they comprised about 80% of the biomass of the lake.

Although the fauna of Lake Victoria was highly interesting and special from an ecological and evolutionary point of view as it represented evolution in action, it was not so from an economical point of view. The cichlid fish, though abundant, were rather small and bony, and thus not ideal for exploitation by commercial fishing and export trade. It was desirable to introduce a bigger fish such as the Nile perch.

As one can easily imagine, the introduction of such a large predator will have an enormous impact on the ecosystem and is likely to transform its structure. Over the rather short period of their evolutionary development into the various species, the small cichlid fish did not have to adapt to large predators (since there were none in Lake Victoria) and were rather defenseless to the threat the new species represented. Therefore, the fears and expectations among ecologists were that after an initial explosive boom of the perch population, the cichlid fish would quickly be driven into extinction, which would leave the Nile perch without food and cause its own disappearance. The net result might be a radical impoverishment, even a collapse, of the eco-system, and a total disruption of the fishing activity.

The first consequence followed as predicted. The Nile perch population really boomed and drove the cichlid fishes to the edge of extinction. But then the unexpected happened:

> Nile perch in open waters continued eating fish until there were virtually none left. But where were the thousands of starving Nile perch floating moribundly on the water's surface? Why hadn't their number declined rapidly? Why had the predicted collapse of the Nile perch population not taken place? [41, p. 226–227]

Rather surprisingly, the Nile perch did not follow the cichlid fish into the extinction but settled on a sustainable population number, because the disappearance of the cichlid fish produced unforeseen side-effects favorable to other species in the lake. The fresh water prawn, for example, used to be a rather marginal player in the eco-system, at least with respect to population numbers. With the disappearance of the detritus eating species of the cichlid fish, a niche opened for the prawn to occupy; in consequence the prawn population increased dramatically. The Nile perch, in turn, facing a shortage of cichlid fish, incorporated the prawn into its diet. Other species, such as the indigenous sardine, the *dagaa,* adapted in similar ways to the new situation, and took over some of the ecological niches the cichlid fish had before. Note that the increase of the prawn and the dagaa was not only a result of the disappearance of a competitor for food, but a genuine adaptation to a previously neglected food source.

Every definition of a system partitions the world into two parts, namely the *system* and its *ambiance.*

We stop at this point of the succession of events to conclude that the result of the introduction of an alien species into the ecosystem of Lake Victoria was its complete and unexpected transformation; to express it in the language of dynamical systems theory: the perturbation of the system resulted in its settling on a new, unforeseen attractor, with different species occupying different niches.

An ecologist trying to predict the outcome of the introduction of the Nile perch into Lake Victoria (or the new attractor of the system) would most certainly have made a wrong guess [42]. At least one reason for this is that the agents of the system (that is the prawn, the Nile perch or the cichlid fish) are autonomous and highly adaptive and there are many different types of them; furthermore, the agents are connected by a net of intense interactions and mutual dependencies; changing one part of the system, such as adding a new predator, might trigger a cascade of adaptations in the system. It is also clear that there are strong nonlinearities in the system. As Goldschmidt puts it, a "man with a bucket" (to plant the fish) was sufficient to invoke a major ecological transformation of the largest tropical lake on earth.

One can conclude that the following properties were important generators of complexity in the eco-system of Lake Victoria:

- Internal inhomogeneity of the system (i.e., it consists of a number of different classes of autonomous agents).
- Adaptivity of agents in the system.
- Nonlinear interactions between parts of the system.
- Net-like causal structure of the system (high connectivity).

Those features do not only seem to be major contributors of complexity in this in eco-systems in general, but have been repeatedly identified as crucial in much more general contexts. Systems with these features are often subsumed under the more general heading of *complex adaptive systems* (*CAS*) (see especially Holland [4,15] and Casti [3]).

Thus, Lake Victoria is complex at least to the degree that it is a CAS. Such systems have been repeatedly described as basically inaccessible to analytical modeling approaches, but CAS have the convenient property that they can, at least in principle, always be modeled by ABMs. We shall now reflect for a moment upon the practical process of constructing an ABM of Lake Victoria to identify some strengths and limitations of the model approach. Perhaps the first limitation that comes to mind is the mapping of the real system onto the model system: Often it is difficult to measure all relevant parameters accurately or to properly understand the dynamical interconnection of certain variables; another important constraint on computer models is the limited availability of human, financial, and computational resources. More relevant to the central problem of this article and therefore the sole focus of our subsequent discussion are limitations that are inherent to the very idea of a model itself. We shall explain this in the following paragraphs.

INTRINSIC LIMITATIONS OF MODELS

Before we continue the discussion we have to make a short remark on our use of the word "system." Following standard usage, we will have to attach two meanings to this notion. In the intuitive sense of the word, a system is a set of phenomena that shares some common aspect one is interested in. Systems in this sense are economic systems, or the ecological system of Lake Victoria, or the political system of the European Union. This notion is somewhat fuzzy, but is at the same time a very intuitive way to refer to certain domains of the world that are interesting for further scientific investigations. We will often refer to systems in this sense as "natural" or "real systems."

The rough identification of a natural system is but the first step in any scientific modeling enterprise. In order to construct a workable model the scientist will have to select a relatively small number of elements of the system which he deems to be relevant. Those elements can now be formalized (either into mathematical equations or computer code). This formalization constitutes what we call the *model.* The elements of reality that correspond to this formalization are what we, for lack of a better word, call the *system* in the impoverished or idealized sense.

Every definition of a system partitions the world into two parts, namely the *system* and its *ambiance.* Importantly, the idealization process that leads to a model does not only involve the simplification of the internal dynamics of the system, but also an idealization of the system-ambiance interactions either by ignoring them all together, or by modeling them in terms of sinks (output) or sources (input). No equivalent of ambiance can be present in the model *as ambiance.* If it were, it would simply have comprised an extra element of the system, enlarging the system boundaries. If there are any interactions with the ambiance that are relevant to the problem at hand, and an enlargement of the system definition is not possible (for whatever reason), then the ambiance has to be internalized into the model in a reduced form, by introducing sinks (output) and sources (input), for example, energy flows and material inflows. In effect, what originally was a number of ambiance interactions then becomes transformed into internal elements of the model (parameters, variables, agents, and the like). For reasons that will become clear below, we will call those kind of models and their corresponding systems *nearly closed.* Typical examples of nearly closed systems are "open" systems of thermodynamics.

It follows from the definition that contextuality is a property that is a direct consequence of the partitioning of the world into system and ambiance preceding any modeling enterprise.

Note the fundamental difference between real systems and the idealized systems (systems in the impoverished sense) that correspond to models. The former are embedded in an external world and their existence depends on a number of circumstances that can and do change on some time scales, to the extent that the system may cease to exist or is transformed in almost any imaginable sense. Models are not embedded anywhere, defining their corresponding (idealized) systems as effectively selfsufficient, although to some degree mutable by modulation of the inflow. We will later on find that this aspect of models is a fundamental limitation to the representation of complexity in ABMs. The only way to overcome it is to construct global models, which would have internalized everything. Needless to say, global models are not realizable. To model systems as essentially closed is therefore intrinsic to the modeling process.

Often, however, it is possible to find system boundaries and time scales which allow an effective internalization of the ambiance interaction as sinks and sources without having to compromise unduly on the scope or precision of the model. The main question of this article is whether this can actually only *often* be done, or indeed always.

STEPPING BACK: THE BROADER VIEW

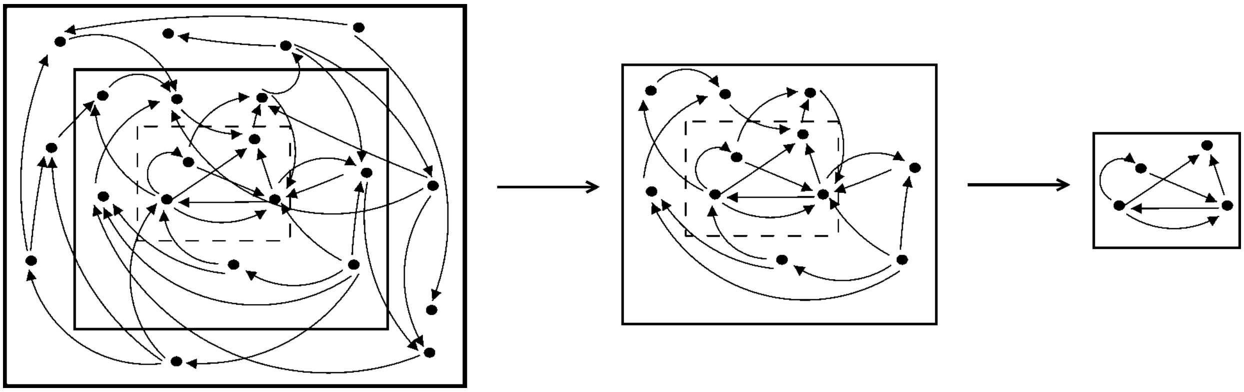
It follows from the above section that modeling presupposes the possibility of a successful identification of a well-defined system and its ambiance. We will now discuss types of conditions under which this assumption actually breaks down, and for this purpose we introduce the concepts of *contextuality* and *radical openness* and explain their content by using the example of Lake Victoria. We will conclude that the above assumptions break down whenever contextuality or radical openness is irreducible.

Radical Openness

The loss of the cichlid fish was not only a sad event for the ecologists who value the biodiversity of our planet, but it also had impact on the economy in the lake region and the life of the people in the area in a direct way. The introduction of the Nile perch was not only an event in an ecological system, but its consequences propagated to other realms of the world. This was possible because Lake Victoria is a *radically open* system, radical because its openness goes beyond what can be represented by sinks and sources in a model. In the following paragraphs we will introduce the concept of radical openness by means of the example of Lake Victoria.

The traditional food-fishes for the people in the Lake Victoria region used to be the cichlidae because they were abundant and cheap to buy (an essential requirement in one of the world's poorest regions). Although the cichlidae are well-suited fish for local consumption, their small size and boniness prevents them from being exportable fish. The Nile perch on the other hand is a valuable fish yielding high market prices internationally, but it can hardly be sold to local people. Exports to Europe and the Middle East promise much higher profit rates. Evidently, local fishermen lack the capital and the knowledge to organize intercontinental export businesses, and traditional catching techniques are not well suited for large scale Nile perch-fishing. Most of the fish is therefore caught by nonlocally owned companies that have the necessary means and machines available. Here we already notice the first signs of radical openness (Figure 1): The original reason to introduce the Nile perch was an economic one. In this sense, the economic system is partly embedded in the ecological system of Lake Victoria and impacts on it; cause and effect chains propagate from the economic system into the ecological system. The economic system transforms the decline of the population numbers of the small cichlidae led to their disappearance from the local food markets while increasing numbers of the Nile perches did not find their way to the local markets (too expensive for the local people and also unsuitable for conservation by sun-drying). Catches

FIGURE 1



Radical openness: If the box at the right side of the figure is a model of a system representing some elements and interactions between them, then in reality this modeled system will be embedded in a larger system (the middle box). For the purpose of the model, the additional interactions that are represented in the middle box might be irrelevant. The left box might now again be thought of as a further opening up of the middle box. If this process of opening up cannot be successfully terminated until we have a global model, the system is radically open.

by local fishermen are mostly sold, for good prices, to up-market restaurants in the area or to factories which prepare the fish for export. For local consumption remain mainly the dagaa and the occasional Nile Tilapia for those who can afford it. Thus, although fish export profits for the countries surrounding Lake Victoria were indeed boosted and local fishermen also can be viewed as being better off because of the higher earnings the Nile perch generates, the general population seems to be on the losing side. With the cichlid fish they have lost an important and cheap source of daily protein.

The transformation of the ecology of the lake, very much motivated by economical deliberations, had an effect on the daily food intake of the people in the lake region. In principle there were more fish in the lake, but less affordable fish. This might again have some long-term consequences for public health (especially through malnutrition), which again might have some consequences for the economy. We see thus, that as much as an economic system transform the ecological system of Lake Victoria, so does the ecological system act back on the economic and social system.

Radical openness is also illustrated by another incident: In the period immediately following the near elimination of the cichlid fishes, an explosive increase of mosquitoes around Lake Victoria was observed. The disappearance of the cichlid fish (of which some species were important predators on its larvae) allowed the insect-population to increase significantly. Obviously, high numbers of insects are a major nuisance to the people living in the area. From time to time huge clouds of tiny insects are blown from the lake landwards; the clouds are at times so dense that it becomes hard to breathe. The introduction of the Nile perch thus also had an effect on the mosquito population, which in turn directly affects the life quality of the people, leading them to consider what to do to solve their problem.

Those two examples show that the ecological system of Lake Victoria is embedded in an ambiance that is impacted by the lake and at the same time impacts the lake. The ecosystem of Lake Victoria is tightly woven into a net of interconnections and mutual dependencies with a large number of surrounding systems of all types. The introduction of the Nile perch caused a major change of the ecological system of Lake Victoria. These changes then lead to changes in the structure of the local economy, even to the establishment of new economic activities (fish processing); but it also led to new dietary habits of the local population and insect plagues. Eventually those changes fed back to the system, for example, through increased fishing activity. We observe a mutual transformation of economic, social, and ecological systems at a number scales.

We suggest that contextuality in radically open systems is a major source of unforeseen and potentially detrimental side effects of interventions into complex natural systems.

Radical openness is a direct consequence of the richness in the connections between real systems and their ambiance. The radical openness is reducible if the ambiance interaction can, for specific modeling purposes (especially on specific spatial and temporal scales) be internalized (sinks and sources) by some choice of system boundaries. An important case of irreducible radical openness are systems that transform their ambiance and are transformed by it on a relevant temporal scale. Let us stress two important properties of this mutual transformation: One domain of the world (such as the ecological system of Lake Victoria) undergoes changes, either induced by the internal dynamics or by some external intervention (introduction of the Nile perch). Because this domain is connected to other domains in various way, the effects of those changes might propagate through the system and out into other domains of the world, inducing changes of various degrees on all scales (particularly if the system is nonlinear, which is the case with most natural systems). Those effects might eventually travel back and lead to the disappearance of the original domain or transform the dynamics.

Internalizing more and more of the ambiance into the system-definition (i.e., repartitioning the world into a new system-ambiance pair) will not make it less radically open or eliminate the interaction with the ambiance but will create another radically open system (compare Rosen [43] and Figure 1); this larger system will contain the old system and parts of its ambiance. For particular modeling interests, some choices of system boundaries might be better than others and actually approximate *quasi-closed* systems on some spatial and temporal scales; in such cases one may call the radical openness reducible. It is the skill of a modeler to find these boundaries, because they define the domain of successful and efficient modeling.

ABMs and all other types of formal models are never radically open (see section 3): First, they are well defined and thus have clear boundaries; furthermore, they are self contained, in the sense that any transformations or state changes of the system or parts of it are internal or due to a well-defined input function. One can also say that they are as such not embedded in an ambiance but might have internalized a highly abstract representation of the ambiance (sinks and sources). In that case they are open, but not radically open.

Laboratory systems as found in experimental physics or chemistry are examples of realizations of nearly closed systems. Indeed, the idea of laboratory systems is to spatially confine and clearly separate and isolate them from their ambiance (apart from strictly controlled inflows/outflows of energy or matter). For the quality of any experiment, accurate control of the background conditions of laboratory systems is essential; in effect, all efforts are made to avoid radical openness. Accordingly, there is always a tradeoff between reproducibility on one hand and the risk of having studied something overly artificial and irrelevant on the other—that one has seen nothing but “artifacts” [44].

Contextuality

One and the same natural system may be studied and modeled using a number of different approaches. Accordingly the models will focus on different aspects of the system and will be motivated by various interests, research programmes and problem definitions. One might, for example, model Lake Victoria as an economical resource, ecological system, as a part of a larger ecological system and so on. There is thus a family of overlapping possible and actually realized models. This is the source for what we will call contextuality. We will call a system *contextual* if it

- includes one or more elements that also occur in a different system(s) or if it is itself a shared element between more than one system
- In this other system(s) the shared elements take part in causal processes different from those included in the original system.

Radical openness and contextuality are properties that make the control and prediction of complex systems very difficult.

It follows from the definition that contextuality is a property that is a direct consequence of the partitioning of the world into system and ambiance preceding any modeling enterprise (Figure 2) Likewise, it is easily seen that global models will not be contextual.

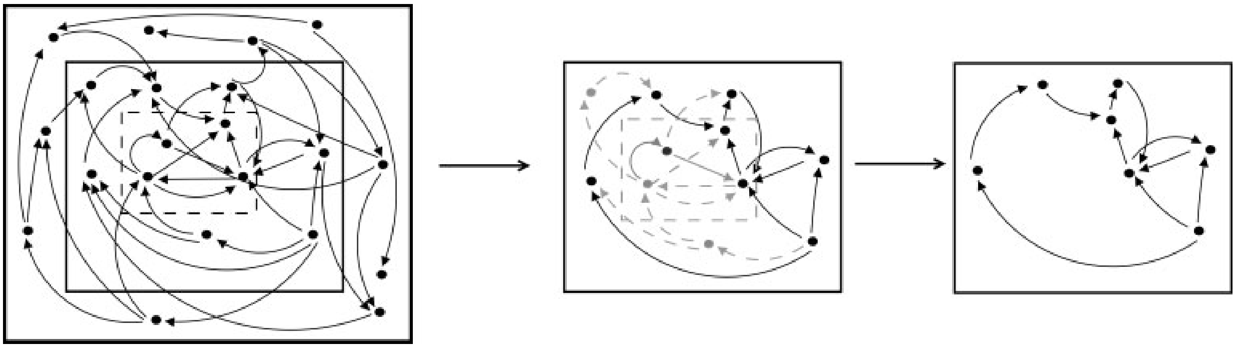
Contextuality is reducible if the contextual properties of a system can be disregarded for all practical purposes. For example, the contextual properties might take place on a very different temporal (or spatial) scale. In this case, no consideration is necessary. The contextuality of the system might also be purely internal (that is, there are no contextual features with other systems that lie in the ambiance). Furthermore, there might be no causal connection between the phenomena of interest in the system and the contextual features of the ambiance. The ecology of a fish tank, for example, is of reducible contextuality; similarly, laboratory systems have only very impoverished forms of contextuality. Furthermore, an ABM has internal contextuality only, but by its very nature no contextuality with its ambiance (because it has no ambiance).

Although certain visions of a unified TOC are unrealistic, the search for common denominators of complex systems is in itself of great scientific importance—indeed, it is a leitmotif of the science of complexity as we see it today.

In real systems contextuality manifests itself often through the fact that its elements play multiple roles, fulfilling several functions across the boundaries of systems. In a certain sense, contextuality is an ubiquitous phenomenon: Given any part of the world, it is always possible to find a host of different partitions resulting in different system definitions, i.e., establish some form of contextuality.

Note that contextuality is conceptually independent from radical openness. Consider, for example, a classical pendulum. On one hand, one may easily figure out circumstances under which it is radically open (for instance as part of a clock device and manipulated by a human being). On the other hand, also when it is shielded from outside influences and accordingly not radically open, it possesses contextuality. The pendulum can be described as possessing a mass, length, and an associated frequency and amplitude, properties that are central to the typical use of a pendulum as an experimental system. It will in addition have other properties, including optical and chemical ones. Those properties are contextual in the sense that the physicist could choose to

FIGURE 2



Contextuality. The box on the right hand side represents another possible model of the system symbolised by the left box in Figure 1. Compared to the model in Figure 1, the modeler takes now a different interest and constructs a different model. However, notice that the two models share the elements inside the shaded dashed box in the middle. Note that those shared elements occur in different contexts in the two models.

model them, instead of the classical pendulum properties of the system. However, the contextuality is wholly reducible in the sense that there is (normally) no interference between the optical or chemical properties and the pendulum motion. Accordingly, we can treat the system as noncontextual (except that we often rely on the contextual properties for its precise measurement).

Admittedly, in this example contextuality degenerates to a trivial property as is the case in many laboratory systems. Degenerated contextuality actually is desirable in this context. The experimental scientist is usually interested in a specific phenomenon, and wishes to exclude the manifestation of others (as they would interfere with his results and ambiguate the interpretation of the experimental data). High, nontrivial internal contextuality of laboratory systems would lead to interfering effects ("artifacts") that would ambiguate the interpretation of the data.

ABMs can display *some* contextuality, and this might actually be one of the causes why they have proven useful. It is obvious, though, that the contextuality in ABMs is purely internal because there is no contextuality with the ambiance of the model, simply because the ambiance is not represented. We believe that reducible contextuality might actually be the source for one of the major fundamental problems in Artificial Life research [45,46]: Currently there are no artificial systems that display open-ended evolution; limitations of the genotype-space are certainly not the reason for this limitation, as is shown by model systems with agents that are constructed programmes written in a Turing complete instruction set, such as Ray's Tierra [47]. It seems therefore that some intrinsic properties of the worlds inhabited by the agents is a factor [48]. We suspect that poor contextuality and a consequent lack of side effects of adaptations of agents is one of the reasons of the poor evolutionary potential of those models. We leave the exploration of this aspect to future work.

We suggest that contextuality in radically open systems is a major source of unforeseen and potentially detrimental side effects of interventions into complex natural systems. In particular when radical openness is irreducible, the side effects may transgress all imagined system borders and propagate to seemingly unrelated areas, as it happened at Lake Victoria (ecological, social, and economical aspects).

The events at Lake Victoria are just one example of irreducible contextuality. The Nile perch is an economic asset/food fish and ecological agent. These aspects of the fish become important in different contexts but are possessed simultaneously. Similarly the cichlidae are a cheap protein source/predator on larvae/competitor for resources for the prawn/prey for the Nile perch. The mosquitos are prey for the cichlidae/nuisance for the people. Furthermore the people are economic agents, but at the same time they are citizens with broad registers of political and other action.

As far as contextuality is concerned, the main question for the modeler of complex natural systems is whether the specific aspects he chooses to take into account in his model are sufficient to understand all the consequences they cause. Failure to do so typically results in unrealistic models. An economist who fails to acknowledge that the Nile perch is not only an economic resource, but also a fierce predator on the cichlids, which are again connected to the mosquitos and to the people and so on, will not be able to understand the consequences and costs of the introduction of the Nile perch. On the other hand, it is clear that prospectively it is hard to come to a full appreciation of contextuality in real systems, although it retrospectively might seem obvious [42].

ELEMENTS OF A TOC: SIX GENERATORS OF COMPLEXITY

Radical openness and contextuality are probably present in most natural systems. In some cases they will be reducible and the modeler can ignore those two features and still produce good and valuable models, just like the physicist can ignore the omnipresent friction (or any other higher-order

TABLE 1

Degrees of Complexity and Models

Areas of Applications	Examples	Features	Models
Policy related issues; when the overall impact of of intervention into the world is to be estimated, but also reconstructions of evolutionary development. Others	Lake Victoria	CAS + radical openness + contextuality	??
Real systems, as long as radical openness and contextuality are reducible.	Evolutionary systems, road traffic systems, business simulations, but also the ecological system of Lake Victoria	CAS paradigm (nonlinearity, adaptive agents, internal inhomogeneity, net-like causal structure	ABMs, neural networks, evolutionary computing, etc.
Laboratory systems and limited applicability to real systems	Physics, chemistry, engineering, classical economic theories	Platonist/Galileian paradigm	Linear differential equations, analytic mathematical models

Physics is the science of the simple. Its models are mathematical and can often even be solved analytically, but in exchange largely linear and only capable of grasping highly homogeneous systems. ABMs grasp a higher level of complexity as they can represent adaptive, nonlinear and inhomogeneous systems. A still higher level of complexity is reached when the contextuality and radical openness of systems is irreducible. Such systems are beyond the reach of ABMs. We currently do not have any effective modeling paradigm for this highest level of complexity.

perturbation) without substantially compromising the validity of his models. There is no reason to believe, however, that this always will be the case. There might be a number of natural systems not only characterized by an intricate internal dynamics, but that also have the potential to interact with neighboring systems to the extent that it transforms them and it becomes itself transformed by them. To account for those unmodeled interactions the system boundaries have to be enlarged; however, if radical openness and contextuality are irreducible, then this will usually not resolve the issue, because the new enlarged model will still neglect the ambiance of the system and thus not be capable of representing the consequences of external contextuality, unless it is a global model. Such transformations would appear to be a manifestation of complexity, and accordingly we find it fair to say that radical openness and contextuality are additional generators of complexity.

Altogether, the example of the introduction of the Nile perch into Lake Victoria allows us to identify six generators of complexity. This list is to be regarded as a minimal set, in the sense that a candidate for a unifying TOC should at least account for all those features, possibly together with additional ones that have been neglected here. If a system possesses only the first four of those generators of complexity (internal inhomogeneity, adaptivity, nonlinearity, net-like causality), one essentially deals with CAS. The degree of complexity involved is usually beyond the reach of the conventional methods of physics, but ABMs (and other approaches to complex systems, such as neural networks, genetic algorithms, etc.) have proven to be powerful methods in this context (Table 1). This is also the realm of earlier successes of ABMs.

But there is more to complexity; this addition cannot be adequately represented in ABMs, because by their very nature they are not radically open (see section 3) and can therefore only represent reducible contextuality. This does not mean that ABMs cannot be usefully applied to systems that are complex in this extended sense; it only means that one has to be aware of the inherent limitations of the model, which stem from the fact that the models cannot represent the full complexity of the system. A similar situation is of course well known from physics where the complexity of the world is ignored to an even higher degree. At the same time, the very existence of complex systems science shows that the over-simplification that we find in physics is of broad applicability, but by no means of universal applicability. Similarly, to approximate the world as not contextual and nearly closed works in many cases, but not always, as suggested by the events at Lake Victoria.

In a practical setting, contextuality in connection with radical openness of a system may manifest itself through dramatic and virtually unpredictable side effects of interventions into the system. In the case of the introduction of the Nile perch, the side effect was an increase of the prawn population, an insect plague and the social and economical consequences of the changing fish stock. We suggest that irreducible contextuality and radical openness are widespread among natural complex systems and become especially important in connection with various types of large-scale practical problems, including environmental protection, governance of economic systems, and policy making, to name but a few [49].

WHAT WE CAN REASONABLY EXPECT

In this section we will bring the different threads of the previous sections together. The question we will pursue is whether the formal and semantic constraints on a TOC identified in the previous paragraphs give some hints about what such a theory could look like. In section 2 we identified a number of formal features of a TOC: It should have a control, prediction or explanatory component, and it should aspire for universality, that is, be applicable to a wide range of diverse phenomena. Moreover, there is the indispensable condition that it addresses the complexity as observed in natural systems. This in turn, as argued through the last sections, means that contextuality and radical openness must somehow be taken into account.

We will find those constraints to be incompatible, that is, there can be no TOC that fulfills all of them simultaneously, except possibly a weak explanatory TOC.

TOC as a Unified Theory in the Tradition of Physical Theory

A TOC is often envisaged as a unified theory in the tradition of the great theories in theoretical physics. To use Holland's words from the above citation, a unified TOC would have to identify "the coherent subject matter" of complex systems science and find the right "level of abstraction" at which its "mechanisms and processes can be given a unified description."

Unification, of course, would mean to find some kind of abstract essence, some kind of universal property that is common to all complex systems. One may note a certain degree of paradox because such visions historically are associated with a Platonist/Galileian paradigm of science, "the science of the simple," whereas complexity science in other respects often distances itself from this tradition [50]. At any rate, the central question is whether there really is some essence of complexity that can be exploited to formulate a Platonist/Galileian TOC. The answer remains unknown.

Indeed, if radical openness and contextuality are essential to the understanding of at least *some* complex systems, this is likely to pose a substantial problem to any attempt to formulate a Platonist/Galileian TOC. The bottom-line of radical openness and contextuality is the acknowledgement that the "agents" in the world are multifaceted, and any reduction of theirs to only one property is a particular choice that can only be justified by pragmatic and case-specific considerations. The search for a *unified* theory of complex systems, on the other hand, is a scientific enterprise which is largely motivated by a Platonist/Galileian ideal of science, to which such pragmatic considerations are quite alien.

Radical Openness, Contextuality, and Prediction

Radical openness and contextuality are properties that make the control and prediction of complex systems very difficult. Already CAS-type of systems are often hard to predict and control, although there are some exceptions (see e.g., the Transims project [12]); in the presence of contextuality, the risk of unforeseen side effects increases. If in addition the system is radically open, these side effects might propagate uncontrollably over system boundaries.

We believe that theories and theoretical understanding of complexity will be important for the proper management of such problems; however, the question to be answered in this article is whether a unified TOC can be helpful in this respect. In particular, can a unified TOC be helpful in deciding how to draw the system boundaries in order to capture the essential elements? Furthermore, can a unified TOC be helpful in deciding which interventions with a natural system will lead to detrimental side effects and which will not (control component)?

We think that it cannot. Side effects are a main cause of scientific uncertainty and a consequence of contextuality. The contextuality of a system is of course case specific and can thus not be derived from a general theory (see in this context [42]). Similar arguments apply for the case of a predictive TOC.

Radical Openness, Contextuality, and Explanation

In our view, the prospects of an explanatory TOC are better than those of a universal predictive TOC. The question is, what exactly it should explain. We cannot expect a TOC to explain exactly why the cichlid fish was driven into extinction, whereas the dagaa was not. Such a TOC would face the same difficulties as a predictive TOC. Rather than trying (in vain) to offer a unified framework applicable to any specific case to explain the particular features of the system, one could aim at identifying general mechanisms common to all complex systems.

There have been a number of suggestions in this direction, including self-organized criticality and the identification of the edge of chaos with complexity. The identifications of these mechanisms could have led to (mathematical) theories explaining the occurrence of certain features putatively common to complex systems (as e.g., statistical distributions). It seems fair to say, though, that none of these attempts can claim to account for all complex phenomena. And even if one happens to find some universal property of every complex system, for instance, something analogous to scaling relations, it does not follow that this common denominator explains much about the complexity of the systems.

Accordingly, the question is not so much if it is *possible* to find common mechanisms in all complex systems as to which extent these can be theoretically nontrivial if radical openness and contextuality are important phenomena in the real world. The quest for common mechanisms behind superficially different phenomena cannot avoid the flavor of a Platonist/Galileian essentialism that basically assumes that the world in a certain sense "really is" simple. One may of course discuss at length "simple" means; but it hardly means radical openness and contextuality.

CONCLUSION: CHALLENGES AHEAD

Although certain visions of a unified TOC are unrealistic, the search for common denominators of complex systems is in itself of great scientific importance—indeed, it is a leitmotif of the science of complexity as we see it today. In a sense, that venture is the construction of theories of “somewhat complex systems,” looking for simplicity within the complex, producing a lot of important knowledge. The intellectual challenge motivating this article is to remember the limited scope of these approaches, not to police exaggerated claims of universality, but to look for new and complementary approaches to study complexity. One such direction is to focus more on *properties* of complex systems, rather than the details of mechanism. For instance, we would like to encourage empirical investigations into the presence and nature of radical openness and contextuality. A different, but related, issue is Rosen’s critique of the Church-Turing thesis, in which he argued that there is something inherently uncomputable about complex systems [30,46], although it is yet to see how something uncomputable should be imagined and detected. We believe that highly original discoveries could result from research along such lines.

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