THE CONCEPT OF EMERGENCE IN SYSTEMS BIOLOGY

A Project Report

By

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1. Introduction

1.1. Motivation

This work is the result of a six week project initiated by Professor Jotun Hein of the Department of Statistics, University of Oxford and Professor Carsten Wiuf of the Bioinformatics Research Centre, University of Aarhus. Professors Hein and Wiuf approached the three authors of this report (all of us being graduate students studying philosophy here in Oxford) with a brief to conduct a philosophical investigation into the ways in which the concept of emergence has been employed in modern biology, more specifically systems biology. (What systems biology amounts to, and just how if at all it differs from other branches of biology, is of course a contentious issue in and of itself, and it is not one we intend to settle here. See Alberghina and Westerhoff (2005) for a useful introduction.) The problem, as we understand it, is that terms such as 'emergence' and 'emergent property' have recently achieved a widespread currency in some scientific journals, while few of the authors who employ this vocabulary offer any kind of definition of what they take emergence to be, or explain why it should be important to the modern scientist. Where definitions are provided they are sometimes lacking in clarity, and sometimes conceptually inadequate. Our aims therefore are twofold: (i) to offer definitions of emergence and related concepts which are philosophically rigorous and which capture the sense in which emergence is employed in modern biology; (ii) to explore the usefulness of the concept of emergence for practical science.

1.2. Quick Guide

In the context of academic philosophy, the concept of emergence has a long history in which numerous philosophers have tried to define a variety of different concepts. Immediately after the present section (primary author: Tasker), section 2 (primary author: Matthies) therefore provides a historical survey and considers a notion of emergence which can be termed 'strong emergence'. It is argued on philosophical grounds that strong emergence is potentially incoherent, but in any case the main purpose of this section is to illustrate our view that extant definitions of strong emergence do not equate to the concept of emergence which may be at work in modern biology. Subsequent sections are therefore concerned with a concept which can be termed ‘weak emergence’, which we take to be less philosophically controversial than strong emergence, and to have determinate applications within modern science. The concept of weak emergence is in fact to some notable extent distinct from that of strong emergence, and readers who wish simply to read about emergence in modern biology could skip the first section altogether. (Although a clear understanding of the notion of strong emergence can clarify one’s understanding of emergence in biology inasmuch as one sees what emergence in biology is *not*.) After discussing a range of definitions of weak emergence and highlighting their moderate nature in section 3 (primary authors: Tasker/Stephenson), section 4 (primary author: Stephenson) illustrates our preferred definition by way of a discussion of Conway’s famous Game of Life. Section 5 (primary author: Tasker) then provides quotational evidence, mined from a range of recent papers in biology that have been published in a range of different journals, that our preferred definition of weak emergence has many determinate applications within that domain. The first appendix (primary author: Stephenson) contains a wealth of bibliographic data that provides all the guidance necessary for the interested reader to further their investigation in any one of several important directions. The second appendix (primary author: Matthies) provides a select glossary of philosophical terms that are perhaps unfamiliar to the everyday practicing scientist. And finally, the third appendix (primary authors: Matthies/Stephenson) introduces particular problems that remain and briefly suggests how the project might be continued.

2. Strong Emergence

2.1. The Problem of Life and the British Emergentists

The problem of life is the problem of finding an answer to the question “What is life?” The answer to this question is non-trivial because, inter alia, there are only physical entities according to the prevalent scientific conception of the world. On the face of it, this claim is in conflict with the existence of biological phenomena such as life and consciousness which seem to go beyond mere physical phenomena. This is because living beings are organized in complex and functional ways, which also incorporate the ability to become more adapted to different environments. These so-called *emergent* phenomena represent a challenge to physically-based explanations based upon mechanistic (reductionistic) assumptions.

Emergence is first of all a philosophical term of art. It applies to properties or substances that, on the one hand,

> (D) “arise” out of more fundamental properties or substances and thus depend on those latter properties or substances and that are, on the other hand,
>
> (I) “novel” or “irreducible” and thus in a certain sense independent from, the more fundamental properties or substances.

The general idea behind the claims (D) and (I) is the following: what we are interested in is the phenomenon of two sets of properties/substances, being distinct, yet closely related.

The latter, (I), is the feature that makes emergent properties interesting and singles them out from any odd distinct properties: if emergent properties had nothing whatsoever to do with the lower-level properties, then it would not be very interesting for a system to exhibit “emergent properties”. For instance, we can assemble metal pieces with particular colours. Think of the colour of those pieces as the fundamental properties. Lumped together, the whole sculpture made of all the metal pieces is going to have a certain shape. However, the fact that the sculpture as a whole is cubic has nothing to do with the parts of the sculpture having certain colours. So if we called the shape of the sculpture an “emergent property” of the sculpture as arising of the more fundamental properties of having certain colours, then emergent properties would not be very interesting. So emergent properties have to be related to certain, more fundamental properties in a systematic fashion, not just in any way.

On the other hand, there has to be a certain gap between fundamental and emergent properties. If emergent properties are not sufficiently distinct from the fundamental properties, then their arising is not an interesting phenomenon that would illuminate anything interesting about the world. For instance, if I draw a line around a point such that the line is everywhere equidistant to the point, then the resulting figure is a circle. However, the property "being a circle" is not an emerging property of the line that arises from the property "being equidistant to a point", if "emergent" is to refer to anything interesting. For the fact that the line, which is equidistant to a point, has the form a circle does not seem to illuminate any novel feature of the line, which is very different from just being equidistant to a point.

So (D) and (I) try to single out a certain class of properties/substances as interesting, because they are on the one hand "born" from some class of more fundamental properties and yet add something entirely new to these more fundamental properties, i.e. they are entirely different from these fundamental properties.

The term "emergence" has a history and is firmly rooted in a specific social, scientific and philosophical context that prevailed in the 18th and 19th century. Knowledge of this context might lead to a deeper understanding of the issues in question in science today. It is with this history that we begin.

In the 18th and 19th century the spectrum of answers to the question "What is life" ranged from mechanistic reductions of biological phenomena to the afore-mentioned mechanistic interactions to the vitalists' assumption of a "vital force" in nature, which was not thought to be explicable in purely mechanistic terms. In the former case, we would have a way of accounting for the arising of life out of mechanistic interactions (namely that it is a reductive relation) at the expense of sacrificing (I), the independence of life from the mechanistic interactions. In the latter case, we would have a way of accounting for the independence of life of mechanistic interactions (its being an entirely new vital force) at the expense of sacrificing (D), a way of explaining how this vital force may arise from mere mechanistic interactions. Theories of emergence sought to address emergent phenomena without having to recourse to some type of "vitalism". They attempted to capture both (D) and (I) in their account of life. The first comprehensive picture was worked out by British emergentists of the late 19th and early 20th century.

The British emergentists took their cue from Mill (1843; Chapter 6, §1):

> "All organised bodies are composed of parts, similar to those composing inorganic nature, and which have even themselves existed in an inorganic state; but the phenomena of life, which result from the juxtaposition of those parts in a certain manner, bear no analogy to any of the effects which would be produced by the action of the component substances considered as mere physical agents. To whatever degree we might imagine our knowledge of the properties of the several ingredients of a living body to be extended and perfected, it is certain that nor mere summing up of the separate actions of those elements will ever amount to the action of the living body itself."

The important distinction for what is nowadays termed "strong emergence" is the idea that some causes when they are conjoined produce an effect that is identical to what would have been the sum of effects of each of the causes acting alone (mechanical mode). A paradigm example for this phenomenon is the parallelogram law, which is one of the laws of vector addition. The total effect of two forces F and G acting in concert on a particle p just is the effect of F acting on p followed by G acting on p. The chemical mode is characterized by strong emergence in the sense that the effect of multiple causes taking together is not the sum of all the effects of the causes had they been acting individually.

Mill's ideas indirectly influenced the "British Emergentists". All of the British Emergentists have certain fundamental ideas in common which make up the *ideology* of their accounts. While the *ontology* of a theory tells us what exists according to the theory (for instance: only physical particles, or physical particles and "spiritual" stuff), the ideology of a theory is the arsenal of concepts a theory relies on that cannot be analysed or defined within the theory.

It is common to the ideology of all British Emergentists that the world is divided into various levels with the level being ordered according to complexity of matter, with fundamental particles on the bottom level, and molecules, organisms and groups of organisms on the higher levels.

Corresponding to each level there is a special science giving a theory of that level, i.e. stating the laws governing the things which constitute the relevant level in virtue of the properties of those things. On the very bottom we find fundamental physics investigating fundamental properties and the laws relating those properties on the most basic level. The remaining “special sciences”, chemistry, biology and psychology and possibly sociology following on the higher levels, focus on properties that emerge from complex systems. These emergent properties can be influenced by behaviours at lower levels in this layered approach.

Various concepts related to this ideology of a layered world, common to all accounts of emergence, need to be clarified. They relate to the two components of emergence, (D) and (I), introduced above. First of all, emergent properties always exist *at* a certain level. However, their existence is in certain ways dependent on the relationship between different levels. If certain lower levels do not exhibit a certain structure, then certain higher level properties will not emergence. This is the impetus of claim (D) from above: higher levels (or properties at higher levels) are in some sense dependent on lower levels (or properties at lower levels). This idea is captured by the concept of *supervenience*.

Secondly, while the special sciences describe the laws governing the things-cum-properties *at* a certain level, those laws still depend in certain ways on the relationship between different levels. In order for chemical properties to be causally effective, there must be some fundamental physical particles standing in the right causal relations to each other, since chemical properties are properties of things that are made up off fundamental physical particles, and those must interact in the right way to create the molecules that then enter into causal relations in virtue of their properties. Here there are two different ways of conceiving of the laws at a certain level as related to the laws operating on the fundamental level. Either, one can conceive of the laws (or of some of the laws) at higher levels as the appearance of primitive high-level causation, i.e. as laws that are additional to the laws of fundamental physics. This was proposed by Mill (1843) and Broad (1925). For instance, the causal impact of a crowd of people, according to this view, is something fundamental and cannot be explained by the causal impact of single atoms in the individual people’s bodies. Or, one can conceive of the high-level laws as not adding to the laws operating at fundamental level. On this account, even though there are high-level entities and associated high-level properties and high-level laws governing these properties, these laws do not constitute causal laws which are distinct from the causal laws at the fundamental level, and must be add to them in order to get a complete theory of the causal dynamics of the world. Such an account is more akin to emergentists like Alexander (1920).

The idea that emergence comes with additional causal power can be captured by the term *downward causation.* The notion of downward causation is often evoked to explicate the second component of emergence, claim (I): higher level (or properties at higher levels) are in some sense independent from lower levels (or properties at lower levels). Thus, accounts of emergence which do not invoke downward causation need some other way of accounting for the independence of emergent properties from lower levels. Those accounts may be weaker by positing something less metaphysically substantial than downward causation. For instance, we might think of (I) as positing some form of epistemic independence, such that emergent properties are predictable only with difficulty/only by an ideal agent etc. from the properties at lower levels. For now, we shall not be interested in epistemic accounts of (I), but only in the very strong characterization of emergence which is based on a metaphysically substantial notion of independence.

2.2 Philosophical and Conceptual Foundations

2.2.1 Epistemological and Ontological Accounts of Emergence

Ontology gives an answer to the question: what is there/ what kind of entities, properties, substances etc. exist? Epistemology, on the other hand gives us an answer to the question: what do/can we know, how do we come to know certain things?

Accordingly, there is a two-fold distinction in the concept of emergence. Emergent properties can be understood as "new" properties, ontologically speaking. That is, they can be understood as adding something to the furniture of reality. Or they can be understood as "new" properties, epistemologically speaking. That is, they can be understood as adding something to our knowledge of reality. (In both cases, however, they will have in common that they are somehow dependent on the more fundamental properties.)

Epistemological accounts of emergence, accordingly, characterize the concept of emergence not in terms of what comes into existence, but in terms of what we can know about the behaviour of complex systems. Epistemologically emergent properties are thus properties of a system that we wouldn't know the system to have, given only our knowledge of the parts of the system and their interactions. Epistemological emergence thus also tries to captures (D) and (I) from above: on the one hand, the "new" properties are related to the more fundamental properties, but they are also independent, where this independence (I) is now cashed out as an epistemological independence related to what we can or do learn based on what we already know.

There are two main characterizations of epistemological emergence:

> *Predictive*: Emergent properties are properties of complex systems which we could not predict the system to have, when all we know is the properties (and the laws governing those properties) of the parts of the system.
>
> *Irreducible-Pattern*: Emergent properties are properties of complex systems governed by true, lawlike generalizations within a special science such that those generalizations cannot be captured in the concepts of physics.

Epistemological emergence is a weaker concept than ontological emergence. For epistemological emergence to hold, nothing new has to come into existence, when parts interact in the framework of a complex system. We do not have to think of emergent properties or entities as somehow being miraculously created once a certain complexity is reached. They might have been there all along and we might just not have known about them before observing the complex system from which they have arisen.

This leaves us with the task to account for the nature of the ignorance that is involved in epistemological emergence. This could be the ignorance of human beings with their limited faculties. Or it could be the ignorance of omniscient beings like God (or, in non-religious terms, ideal cognizers), or anything in between. Depending on how strong we construe the ignorance, we can distinguish between strong and weak(er) epistemological emergence. Strong epistemological emergence claims that not even an ideal cognizer could come to know which properties will emerge from a complex system, even given his knowledge of the parts of the system, their interactions with each other and their interaction with the environment. Weak epistemological emergence on the other hand merely claims that beings with weaker epistemic faculties could not (or even just do not) know which properties will emerge, given their knowledge of the parts of the system, the interactions of the parts with each other and the interaction of the parts with the environment

If it turns out that ontological emergence is metaphysically untenable, then this task of accounting for epistemological emergence becomes especially pressing. First, however, let us consider ontological emergence.

Ontological emergence characterizes emergence not in terms of what can be known or predicted, but rather in terms of what there is, in addition to the level of fundamental particles and their properties. It is this kind of emergence that was the focus of the British emergentists who conceived of the world as constituted by layered strata. According to ontological emergentism, emergent properties are “novel” properties that come into existence at higher levels of the layered world. They are new in the sense that they are not reducible to the properties of the lower level, in particular the level of fundamental physics.

Thus, we derive at a prima facie characterization of strongly emergent properties of the ontological sort, invoking the notions of supervenience and irreducibility (Chalmers 2006, Kim 2006):

Strongly (ontologically) emergent properties:

> (DS) supervene on the properties of more fundamental entities,
> (IS) are not functionally reducible to more fundamental entities.

(IS) expresses the novelty and independence of the emergent properties. Different accounts of this independence are possible. Another way of stating (IS) is thus in the terminology of necessitation on the level of truths, rather than properties:

> (ISN) High-level truths concerning strongly emergent properties are not conceptually or metaphysically necessitated by low-level truths

(IS), as stated here, is a purely negative way of cashing out the independence of emergent properties. It only makes a claim about what they are not, namely they are not reducibly to other properties. In order to give a positive account of (IS), the notion of downward causation is often invoked:

> (ISC) Strongly emergent properties exhibit downward causation**.**

McLaughlin (1997) defines emergent properties as follows: "If *P* is a property of *w*, then *P* is emergent if and only if (1) *P* supervenes with nomological necessity, but not with logical necessity, on properties the parts of *w* have taken separately or in other combinations; and (2) some of the supervenience principles linking properties of the parts of *w* with *w*'s having *P* are fundamental laws" (p. 39).

(1) in McLaughlin's account corresponds to (DS). The only addition is a characterization of supervenience as involving nomological, rather than logical necessity. We are returning to this in the next section. (2) states another characterisation of (IS):

> (ISL) Strongly emergent properties are linked to the properties they supervene on by fundamental laws.

(ISL) is just a rendering of (ISC) in terms of laws. If causation amounts to the existence of laws, then (ISC) is identical with (ISL). If there is downward causation, then there are going to be laws of nature outside of physics. That is, physics wouldn't not be enough to explain any phenomenon in the universe and there could never be one physical theory of everything.

2.2.2 Supervenience and Irreducibility

As we have seen, supervenience is an important notion in the context of emergent properties, because it explains the link between the levels of the layered world and is supposed to account for the dependence of emergent properties on lower levels.

(S) Roughly, a set of properties A supervenes upon another set B just in case no two things can differ with respect to A-properties without also differing with respect to their B-properties. Or, more briefly: "No A-difference, without a B-difference".

For instance, consider coloured mosaic stones that are arranged in a box such that the result is a picture of an animal. When we next look, we see a picture of a mountain. But this just means that the stones must have been re-arranged when we didn't look. There could not be a different on the macro-level, the resulting picture, without a difference in the micro-level, the location of all the stones, taken singularly.

It is important to note the modal term "can" in the formulation of (S). This captures the fact that supervenience does not merely say that, as it happens, there is no change in the macro-level without a change in the micro-level (maybe we haven't observed any occasion yet, where the macro-level changes, but the micro-level doesn't, which gives us reason to think that, in general, the macro-level changes, only if the micro-level changes). Rather, supervenience claims are modal claims about what *must* or *cannot* happen. Intuitively, this means that the same emergent phenomena will always occur, whenever certain things act together in a more fundamental way.

However, there are various senses in which something *must* or *cannot* happen. It might not happen, because it would contradict logic. For instance, a lot of people claim that if p, then it cannot – as a matter of logic -- simultaneously be the case that not p. Or, it might not happen, because it would contradict the laws of nature. For instance, a person cannot travel faster than light, not because this would contradict logic, but because this would run counter to what the laws of nature say. Lastly, it might not happen, because it would be metaphysically impossible. For instance, water must be H2O, because it is a metaphysical necessity that water is identical with H2O.

I am not going to discuss the existence or nature of metaphysical necessity and its relationship to logical necessity, since for our purposes it is only important to note that the modal character of supervenience claims can be of different kind, logical, nomological (i.e. the relevant necessity would be that of the laws of nature), or metaphysical. Our interest lies with emergent properties, and they are thought to be nomologically, but not logically supervenient on low-level properties (Cf. e.g. Chalmers 2006).

Supervenience is one part of emergence (captured by claim (DS) above). The other part, (IS), states that emergent properties not only supervene, but are also in a certain, strong, sense independent of the properties of the level they supervene on. We are going to discuss ways in which this strong independence may be cashed out in section 2.2.3. It is already clear, however, that the supervenience relation must have certain negative characteristics, if it is to be compatible with the strong independence, which is demanded by (DS). Namely, supervenience must be a relation between properties that is, first, weaker than an entailment relation. This is because one form of cashing out the independence stated in (IS) is that high-level truths concerning strongly emergent properties are not conceptually or metaphysically necessitated (Chalmers 2006) by low-level truths. Secondly, supervenience must be weaker then a reductive relation. This is because another form of cashing out the independence demanded by (IS) is that strongly emergent properties are irreducible to lower level properties (e.g. Kim 2006). Thus, if supervenience was as strong as, or stronger than, either entailment or reduction, the notion of emergence would run danger of being an inconsistent notion. We are going to consider the relationship between supervenience and entailment and supervenience and reduction in turn.

Strictly speaking, if we talk about entailment, we mean to say that certain statements entail other statements. So while supervenience, as characterized above, is a relation between *properties*, the entailment relation holds between *statements*. We can easily fix this problem though by characterizing a notion of property entailment as follows: property P entails property Q just in case it is metaphysically necessary that anything that possesses P also possesses Q. What is characteristic of an entailment relation? Entailment relations are

(i) reflexive (Necessarily, something that possesses P, possesses P)
(ii) transitive (Necessarily, if it is necessarily the case that if one thing has P, then it has Q, and if it is necessarily the case that if one thing has Q, then it has R, then: it is necessarily the case that if one thing has P, it has R)
(iii) non-symmtric (If it is necessary that if some thing has P, then it has Q, then it may or may not be necessary, that if that thing has Q, it has also P)

Supervenience shares the characteristics (i), (ii) and (iii) of the entailment relation, which we are not going to prove here. But entailment is neither necessary nor sufficient for supervenience, as one should expect, if supervenience is to play the role in an account of emergence that it is supposed to play.

Suppose that B-properties entail A-properties. This is not sufficient for supervenience. For instance, the property "being a brother" entails the property "being a sibling": every brother is also a sibling. But being a sibling does not supervene on being a brother. A counter-example to this would be a situation in which there are two people, with neither of them being a brother, but one of them being a sibling and the other one not being a sibling. For according to (S1), if A-properties supervene on B-properties, then a change in the A-property "being a sibling" must co-occur with a change in the B-property "being a brother". But if John is an only-child, and Mary has a sister, then we have a case, in which a thing has the property "being a sibling" and another does now, without there being any change with the property "being a brother" (for neither Mary nor John are brothers).

Hence, entailment is not sufficient for supervenience. Hence, there are cases of property entailment which are not cases of property supervenience. This does not prove the important point though that there are cases of property supervenience which are not cases of property entailment. Only if the latter claim can be proven, there is room in the concept of emergence for claim (I). If every supervenient property is entailed by properties in the supervenience base, then supervenient properties cannot be independent in the strong sense envisaged by those defending strong emergence.

Entailment is not even necessary for supervenience. In order to establish this, we show that supervenience is not sufficient for entailment. We only have to show this for nomological necessity, since the modality of supervenience claims in the case of emergent properties are of a nomological kind. There are examples for cases, in which supervenience holds with only nomological necessity in which there is no entailment. For instance, thermal conductivity properties do not entail electrical conductivity properties.

We now show that supervenience does not amount to reduction. This is important, recall, since the second component of emergence can be cashed out as stating the irreducibility of emergent properties. Hence, supervenience must not entail reducibility for the sake of consistency of the notion of emergence. There is a close relation between supervenience and reduction. If A-properties reduce to B-properties, then the A-properties supervene on the B-properties. This is because if there is such reduction, then a difference A-properties is a difference in those B-properties to which the A-properties reduce. Does supervenience suffice for reduction? If it does, then this kind of supervenience is incompatible with strong emergence.

Note, first of all, that (S1) says that if A-properties supervene on B-properties, then a change in B-properties is necessary for a change in A-properties (or a change in A-properties is sufficient for a change in B-properties):

> Necessarily (A-properties change → B-properties change).

This can also be expressed as saying that if the B-properties stay the same, then so must the A-properties (because a change in B-properties is necessary for a change in A-properties to occur):

> Necessarily (B-properties stay the same → A-properties stay the same).

(S1) does *not* make the same that if a system is in identical states on the Supervenience level, then the corresponding lower-level arrangements of entities must also be the same:

> Necessarily (A-properties stay the same → B-properties stay the same).

This is in fact the converse of (S1) and incompatible with functional irreducibility. For functional irreducibility entails that one and the same high-order property (A-property) can have different lower-order properties (B-properties) as its realizers. In order for that to be true, it can’t be the case that it is necessary for A-properties to stay the same that the B-properties stay the same. (S1) on the other hand allows for this possibility. All that (S1) claims is that if higher-order properties (A-properties) *change*, there must be something happening with the lower-order properties (B-properties). The only thing (S1) claims about a situation, where higher-order properties (A-properties) stay the same, is that such a situation *can* be brought about by the B-properties staying the same: unchanging B-properties are sufficient for this situation to arise. But something else could also bring about this situation. So even if the B-properties *do* change, it could still be the case that the A-properties stay the same. Hence, functional irreducibility.

Hence, the prima facie impression that supervenience might threaten emergence by entailing reduction is not correct. However, the connection between supervenience and either ontological or epistemological reduction might still be too close, threatening ontological and epistemological emergence, respectively. I am going to consider epistemological and ontological emergence in turns.

As to epistemological emergence, supervenience does not suffice for reduction as long as the occurrence of supervening properties is not knowable a priori, i.e. if the necessity in (S1) is not logical necessity. The idea here is that in order to establish irreducibility we have to drive a wedge between lower-level properties and emergent properties. If the gap between these two different sets of properties is not wide enough, then there is a danger of the emergent properties just "collapsing" into the lower-level properties. If we could know a priori that certain properties would emerge from lower-level properties, then the gap would not be wide enough. Hence, if the necessity in (S1) is logical necessity, then supervenience does amount to reduction and this would be incompatible with epistemological emergence.

However, as we have already mentioned, the modality of the kind of supervenience we are interested in is not logical, but nomological. If emergent properties were to supervene with logical necessity on lower-level states, then this would be knowable a priori on any standard account of logic as something whose results are knowable a priori. But the laws of nature are not knowable a priori, i.e. they cannot be "found" by sitting back in an arm-chair and pure reflection: we actually have/had to carry out empirical research to figure out which the laws of nature are. So supervenience does not threaten epistemological reduction, and consequently does not threaten epistemological supervenience.

As for ontological emergence, we have already seen that if reduction amounts to property identity or entailment, then supervenience is not sufficient for reduction. Hence, ontological emergence is salvaged on these fronts.

Kim (2006) gives an account of irreducibility, which is compatible with (ontological) supervenience. According to Kim, property M is emergent from a set of properties N1…Nn only if M is not functionally reducible with the set of the Ns as its realizer. A property M is functionally reducible with the set of the Ns as its realizer if and only if we can give a functional definition of M in terms of the Ns. For instance, if pain could be defined as the state that is typically caused by tissue damage and trauma and that typically causes aversive behaviour, then pain would be functionally reducible.

2.3 Examples of Strong Emergence

The only examples of strong emergence in philosophy appeal to the world of the mental and consciousness.

The thought is that people are agents in the world and that their actions, which are caused by certain mental events (or so it is often claimed), make a causal difference in the world. Hence, mental properties seem to be primary examples of emergent properties (e.g. Searle 1982).
For instance, if I strongly desire a beer and if I believe that I can get a beer, if I open the fridge, then, all things being equal, I am going to go to the fridge and take out the beer, i.e. my body, a physical objects is going to move in a certain way – and the way in which it moves is caused by something mental, my desires and beliefs. If this is a convincing story, then one conclusion from it would be that mental properties are strongly emergent properties. They supervene on the physical (or rather certain brain states), but they exhibit downward causation, since they can make physical objects like bodies move.

Many philosophers deny that our introspective impression that we can control the micro-level of our brain functions and muscles tissues by our thoughts, beliefs and wishes shows that the latter are examples of emergent properties. They do this for different reasons. Either they accept that the phenomenology of our introspective states in fact suggests that we have control over the micro-level, but dismiss this phenomenological experience as evidence for the existence of emergent properties. Dennett (1987) thus argues that, when it comes to our conscious experience, the phenomenological impression is illusory. That is, we may have the impression that something goes on over and above microscopic processes in our brain – we might think that our perceiving something red for instance is unique and novel. But, so the objection goes, this impression is misguided. We are mislead by aspects of our experience when all there ultimately is are neurons firing. Thomas Nagel (1986; pp. 114-115) and Thomas Searle (1984; pp. 87-88) argue the same with respect to control over action. So not only the "what it's like" aspect of conscious experience, but also the impression that we as subjects causally influence our limbs to move in a certain way is misguided.

Even if we deny that mental properties in general are strongly emergent property, some people (e.g. Jackson 1982 and Chalmers 1996)) still find it plausible to conceive of at least one very specific kind of mental properties as strongly emergent, namely qualia, the “what it’s like” features of conscious experience. Dennett’s (1988) objection, however, would still apply, of course.

It is difficult to find examples of alleged emergence outside the mental realm. Examples here include Ilya Prigonine’s “dissipative structures” (e.g. Nicolis and Prigogine (1977) and Prigogine and Stengers (1984)) of non-equilibrium thermodynamics which supposedly involve properties and dynamical principles that are irreducible to fundamental physics.
Further examples are the “protected” properties – properties that are insensitive to microscopics – of various different kinds of macroscopic matters, such as the crystalline state. These were put forward as examples of properties that are inexplicable in the terms of fundamental physics, but well understood if we consider them under high-level principles, for instance by Laughlin (e.g. Laughlin and Pines (2000) and Laughlin et al., (2000)).

However, it is not clear whether this really is an instance of genuine ontological emergence, or merely an instance of epistemological emergence. It is not clear, whether the high-level principles are favourable on purely pragmatic grounds (they are easier too handle; they are the only thing we have at the moment), or whether it is genuinely impossible to derive the high-level principles from the microscopic structure, even if our science were to advance further, even if we put a lot of effort in the attempt and even if we were not subjected to pragmatic hindrances. Because if it is just for the reasons just mentioned that the high-level properties are inexplicable in the terms of fundamental physics, all we have is an instance of epistemological, or weak emergence.

2.4 Problems for Strong Emergence

2.4.1 Problems with Supervenience and Reduction in an Account of Emergence

Kim (2006) notes that for emergence to be a robust, natural relation we need something more than supervenience and (functional) irreducibility (claims (DS) and (IS)). This is because supervenience allows for different grounding relations and is thus not a robust notion. Consider, for instance, as an analogue the claim that moral facts supervene on natural facts. To know the truth of this claim still does not come to any understanding what morality consists in. In order to give a robust characterisation of emergence, we would have to know the deeper relation that grounds and explains why supervenience holds between two sets of properties. According to classical emergentism this is precisely the kind of information we cannot have.

Irreducibility as functional irreducibility is a merely negative characterisation (absence of reducibility) as well. It just tells us something about what certain properties do *not* exhibit, namely they are *not* reducible to other properties. It does not tell us what emergent properties actually *do* and on what accounts they are *novel*. In order to give a positive account of the notion of strong emergence, i.e. to genuinely account for their novelty, the notion of downward causation is often employed. The reason why emergent properties are independent from the more fundamental properties they arise from, so the thought goes, is that they exhibit downward causation.

2.4.2 Downward Causation

According to Campbell's (1974) account, the principle of downward causation can be stated as follows:

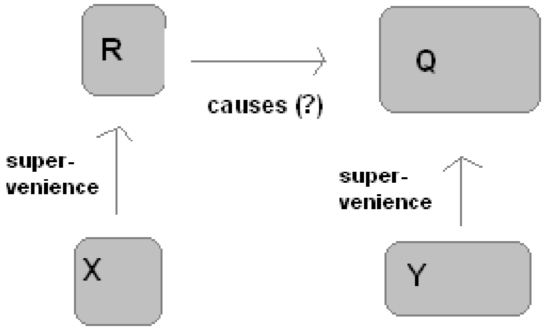
> All processes at the lower level of a hierarchy are restrained by and act in conformity to the laws of the higher level.

Downward causation can thus be defined as a converse of some or other reductionist principle: the behaviour of the parts of a system (down) is determined by the behaviour of the whole system (up). That is,

> the whole is to some degree constrained by the parts (upward causation), but at the same time the parts are to some degree constrained by the whole (downward causation).

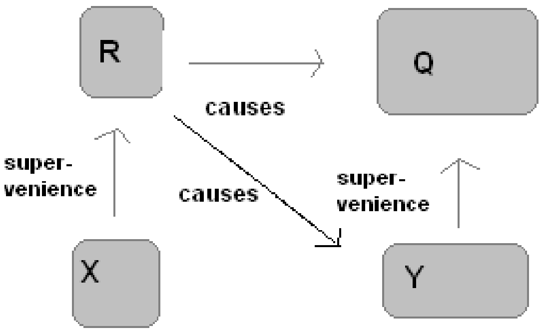
An example could run as follows. Consider a snow crystal that has the strict six-fold symmetric shape all snow crystals exhibit. The particular snow crystal we are considering will also have a unique symmetric shape (no two snow crystals are alike). While the symmetry of the whole system is determined by the (chemical) properties of the water molecules constituting it, once a particular shape has been formed, the shape of the whole is not determined by the properties of its parts. Rather, the location of the constituent water molecules is constrained by the properties of the whole, namely its crystalline shape. It could be said that the whole (crystal) causally influences the parts of the system (the water molecules) by "pushing" them into a certain place, causing them to be in a certain place.

Emergent properties are thus novel in the sense that they introduce novel causal powers to this world. However, it is still not clear why we need downward causation, i.e. causation from higher to lower level, in order to give a positive account of emergence. Why is it not enough for higher-level properties to causally effect other higher-level properties to account for their novelty? The picture would be as follows, with X,Y, R and Q denoting properties:



In this picture, R emerges from R, Q emerges from Y and R causes Q. No downward causation is involved.

However, the following considerations show that the very possibility of causation between emergent properties relies on our understanding of downward causation. In the diagram, Q is causally brought about by R, but it is also brought about by Y, not causally, but because Y forms a low-level property from which Q emerges. So, R and Y both bring about Q, but this means that whether or not R is there, Q will be there anyway in virtue of Y giving rise to Q. But this seems to imply that R causes Q only in virtue of causing the property Q supervenes on, Y. In order to cause an emergent property, there has to be a cause for the lower-level property from which it emerges. Or, put differently, if R didn't have any causal influence on Y, it wouldn't be able to cause Q either. In order to cause pain, you have to cause something that brings about pain – tissue damage, for instance. So the picture would be something like this, now exhibiting genuine downward causation (from R to Y):



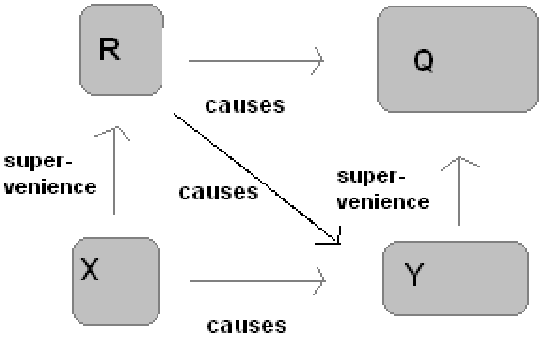
O'Connor (1994) and Humphreys deny that a high-level property can cause another high-level property only by causing the low-level property the latter supervenes on. They do this on the grounds of the claim that emergent properties do not synchronically supervene.

For O'Connor, the conditions on an emergent feature are all prior to its occurrence, as would be true of any primitive property described by physics. And emergent properties themselves can have emergent properties directly at the emergent level. For Humphreys, the 'basal' properties undergo fusion, and so cease to exist in the resulting emergent property. Thus the fusion $P_l^{i+1}[x_l^i](t_1)$ can directly cause $P_m^{i+1}[x_m^i](t_2)$ without first causing the i-level properties which upon undergoing fusion would result in $P_m^{i+1}[x_m^i](t_2)$.

2.4.3 The Problem with Downward Causation

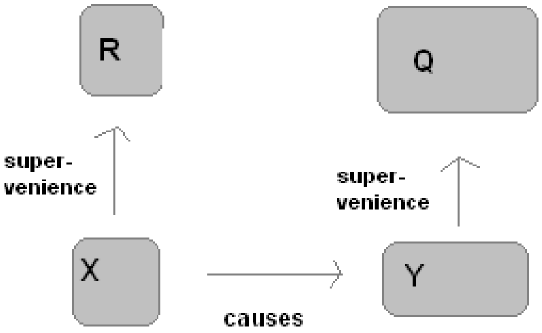
We have more or less introduced downward causation by ways of example. It is not quite clear whether there is such a thing in nature that could be called "downward causation".

However, we do not actually need to settle this very difficult issue here. For even granted there is such a thing as downward causation, this does not suffice for giving a robust account of strong emergence for properties. This is due to what Kim introduced as the causal *exclusion argument* (Kim 1993). The exclusion problem arises as soon as we reflect on the nature of R's (the emerging property's) causing Y. How does R exert its causal influence on Y? And the obvious answers seems to be: R exerts its causal influence on Y in virtue of supervening on some property X, which causes Y on the lower level. Thus, we have the following situation obtaining:

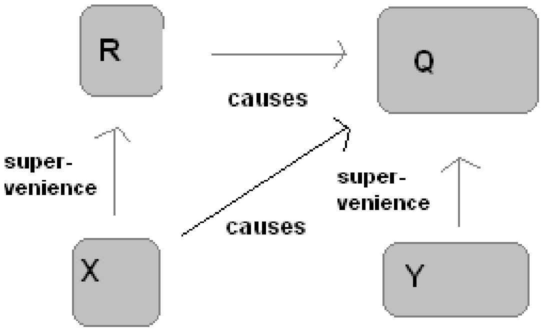


If R causes Y and R supervenes on X and Q supervenes on Y, then, surely, R must cause Q in virtue of X causing Y. However, if this is true, then not only is the causal relation between R and Q apparently redundant in the sense that it is fully accounted for by the causal relation between X and Y, but so is the relation of downward causation between R and Y.

Or rather, either the only causality going on is X's causing Y, in which case we would lose our positive account of emergence involving novel causal powers on the higher level:



Or we insist on a causal relation between R and Q, then we have a case of causal overdetermination (Q is caused both by X (because X causes Y, and Q supervenes on Y) and by R:



Most scientifically-minded people would strongly oppose the existence of causal overdetermination. But it seems that we have to either endorse overdetermination or epiphenomenalism. For in fact, once we have the causal relations at the low level, any causal relation at the higher level must be redundant. Hence, if emergent properties have causal powers or exhibit downward causation and if we exclude causal overdetermination, then they apparently have their causal powers solely in virtue of supervening on properties of lower levels which have causal powers. If this is the case, then the emergent properties are *epiphenomenalist*, just as shadows are epiphenomenalist in the following scenario: If Mary hits the ball, then Mary causes the ball to fly. Assume that the sun is shining and that Mary and the ball have a shadow, which supervene on Mary and the ball. Even though Mary causally effects the ball, this does not mean that the shadow of Mary causally effects the shadow of the ball.

So ultimately we are faced with the following dilemma: either both, low-level and emergent properties have causal powers. That would give us a good account of how emergent properties are distinct of, and independent from the properties they emerge from. But in this case we have to accept causal overdetermination, which many consider to be too bizarre to be taken seriously. Or emergent-properties have causal powers in virtue of the causal powers of the properties they supervene on, emerge from. In this case the emergent properties just seem to be superfluous. This is because properties without causal powers do not seem to do any work in our account of nature. (According to some accounts, which conceive of properties as clusters of causal powers, such properties couldn't even exist.)

There is a lot of discussion evolving around problems related to Kim's (1993) causal exclusion argument. It highlights that the notion of strong emergence is at best very problematic and at worst entirely incoherent. In order to get a viable account of emergence that can play a role in the sciences, it thus seems necessary to look for a weaker kind of emergence that does not have to rely on notions as problematic as that of downward causation. Such an account of weaker emergence is just what is given by epistemological emergence.

3. Weak Emergence

The aim of this section is to formulate a definition of emergence which does not involve any controversial commitments about the nature of the world (like strong emergence seems to), and which captures the usage of the concept of emergence in modern biology. We can at the outset again distinguish two characteristics which are hallmarks of emergence in general. Emergent properties (or we might choose to speak of emergent phenomena, states, conditions, processes etc.) are:

(a) (somehow) *constituted by*, and *generated from*, underlying processes
(b) (somehow) *unpredictable* based on knowledge of their underlying processes

The problems with strong emergence arose out of the incompatibility of these two hallmarks. By conceiving the second hallmark, (b), as an epistemological (as opposed to ontological or metaphysical) condition there opens up a way to resolve this tension: the two hallmarks can be taken to indicate that an emergent property is something which human beings (presumably specifically the scientific community) are unable to predict – not because it is in any strong metaphysical sense autonomous from the underlying processes which give rise to it, but simply because our physiology and the state of our background knowledge does not enable us to understand the connection between the emergent property and its underlying processes. On this conception the unpredictability of weakly emergent properties is just an artefact of our limited powers as human beings. This makes the concept of emergence consistent at the expense of rendering it somewhat context-relative. The properties that emerge are only difficult to predict *given current scientific knowledge and current best methods of prediction*. However, this needn't render emergence useless or philosophically or scientifically untenable. Lots of things are context-relative and yet have highly determinate definitions and applications, and things can be context-relative in entirely unproblematic ways. To make good on this claim we will need some more precise definitions to work with.

One definition of emergence which one finds occasionally in both philosophical and scientific texts, and which we consider to be unable in isolation to capture any substantive or interesting concept, asserts that an emergent property is one possessed by an object such that none of the object's parts have that property. However this does not appear to be either necessary or sufficient part of any interesting definition of emergence. The proposed condition does not seem to be sufficient, because a table can have a weight of 10 kilos though none of its parts have the property 'weighing 10 kilos'. Equally, the condition does not seem to be necessary: suppose we inject a small cloud of gas into a large sealed room. The cloud 'occupies' a certain position if and only if at least one of its constituent molecules is in that position. Then we can say that 'occupying position x' is a property instantiated by the cloud *and* by one of its molecules. The problem is that we may still wish to say that the area of occupancy of the cloud is emergent.

A way to rectify this problem is by looking more closely at the modality involved in the claim that an emergent property is one possessed only at the higher levels. If this is merely a claim about contingent actuality – about whether as a matter of fact such a property is or is not possessed at both higher and lower levels – then the above objection has some considerable force. However, if it is rather a claim about *possibility* – about whether it would even make sense to ascribe said property at the lower levels, or about whether it could ever, given physical and perhaps even metaphysical laws, be possessed at the lower levels – then it becomes rather more interesting. Nevertheless, it is still clear that such a criteria – let us call it 'modally interesting level rigidity' – would probably remain neither necessary nor sufficient.

Let us consider other attempts at providing more central criteria. The following definition is based on Chalmers (2006: 244):

> A high level property is weakly emergent with respect to a low level domain iff the high level property arises from the low level domain but truths concerning that property are 'unexpected' or 'surprising' given the principles governing the low level domain

This gives us the key *epistemic* characteristic but is still a bit vague. More than once during this project we have come across the objection that a property can be surprising when it is discovered but then it must cease to be surprising once its discovery has become widely known. The thought then goes that a property could be emergent one day and non-emergent the next. This seems to render the concept of weak emergence almost entirely trivial. However, this represents a serious misunderstanding of Chalmers' notion of 'surprising'. To illustrate the point we will use an example: Bob's experience of the world informs Bob that many adult human beings exhibit behaviours indicative of a rich inner mental life. There is something surprising about the fact that the physical actions of a human being can be apparently guided by their internal motivations and desires. However, in another sense, Bob has ceased to be surprised that the people he meets exhibit the outward signs of a complex inner mental life. Indeed, Bob has met so many people whose outward behaviour suggests the activity of a conscious mind that he fully expects the next adult he meets to manifest exactly the same behaviour. In what sense, then, is such behaviour surprising?

Chalmers' characterisation of weak emergence is intended to capture the notion that weakly emergent properties are somehow difficult for us to predict or discover. It is useful at this point to make use of a distinction clarified by Kim (1999), between 'inductive predictability' and 'theoretical predictability'. Roughly, a phenomenon, P, is theoretically predictable based on knowledge of some other phenomenon, Q, if detailed knowledge of Q alone would suffice to afford a prediction of P. The complex behaviours which we take to be the outward signs of a conscious mind cannot – as yet – be predicted based purely on our knowledge of the micro-conditions inside their brain. The lines of explanation between what we know of human brains and what we know of human consciousness have not yet been drawn. In this sense, human consciousness is indeed a very surprising thing to find in a world made of physical stuff. Human consciousness, then, (or the complex behaviours which we take to be the outward signs of consciousness) cannot currently be theoretically predicted on the basis of our knowledge of the human brain. However, the sense in which consciousness is not surprising can be captured by the fact that it is inductively predictable. Kim (1999: 8) writes:

> Having observed that an emergent property, E, emerged whenever any system instantiated a microstructural property, M, we may predict that this particular system will instantiate E at t, given our knowledge or belief that it will instantiate M at t. More generally, on the basis of such empirical data we may have a well-confirmed "emergence law" to the effect that whenever a system instantiates basal condition M it instantiates an emergent, E.

Having experienced the fact that many human beings exhibit the outward signs of consciousness, we have come to expect previously unencountered human beings to exhibit similar signs. Our ability to predict this phenomenon is well captured by Kim's notion of inductive predictability. The suggestion here should be that Chalmers' definition of weak emergence can be supplemented with these two different notions of predictability. An emergent property may be unsurprising in the sense that it is inductively predictable; but it should be surprising in the sense that it is not theoretically predictable.

On this view, the fact that a certain property is emergent is still relative to what we know at a certain time. As our knowledge of the human brain improves – that is, as our scientific knowledge increases – it could be that consciousness ceases to be an emergent property. However, we consider this kind of context sensitivity to be harmless. A property does not cease to be emergent just because we have discovered its existence. It ceases to be emergent only when we have fully explained it in terms of the underlying processes which are responsible for its generation. Weak emergence is relative, but far more stable than the objection regarding the common notion of 'surprise' presupposes.

Another way of cashing out the notion that part of what makes a property emergent is that it is difficult to predict can be found in Bedau (1997: 378):

> Macrostate P of system S with microdynamic D is *weakly emergent* iff P can be derived from D and S's [initial] conditions but only by simulation. [Bedau speaks of 'external' rather than initial conditions, a term for which he provides a technical definition. For our purposes it is sufficient – and more intuitive – to speak of the 'initial' conditions of a system.]

This raises the question how to understand *simulation*. Here is what Bedau (1997: 378) says on the matter:

> Although perhaps unfamiliar, the idea of a macrostate being derived "by simulation" is straightforward and natural. Given a system's initial condition and the sequence of all other [initial] conditions, the system's microdynamic completely determines each successive microstate of the system. To simulate the system one iterates its microdynamic, given a contingent stream of external

> conditions as input… [T]he [initial] conditions and the microdynamic completely determine whether P materializes at any stage in the simulation... What distinguishes a weakly emergent macrostate is that this sort of simulation is required to derive the macrostate's behaviour from the system's microdynamic.

Despite Bedau's assurance, we feel unable to give a precise definition of simulation as opposed to 'prediction without simulation'. Nevertheless, the prevalence of computer modelling in modern science might support an intuitive understanding of Bedau's definition. Essentially, Bedau is suggesting that an emergent property is one which we could not predict without constructing a computer model which incorporates the behaviour of the various components responsible for that property's instantiation. This will become particularly relevant in the next section. For now it will suffice to remember a lesson we learned from the easily defused objection to context-relativity. It may well be sufficient to look at the day-to-day practices for experimental systems biologists in order to decide what notion of simulation we want to work with. By doing this we will not find an absolute definition of simulation, but we will find criteria for practical application. And perhaps these criteria will change with time, as a priori calculation methods improve, or as computer modelling methods improve. But this is simply the nature of the case.

So far we have introduced two characteristics – modally interesting level ridigity and surprisingness or unexpectedness or current unpredictability. In general we take the latter to be of absolutely central importance, although the former is by no means irrelevant, so long as it is understood properly. It will be useful to mention briefly three further characteristics that fit into this second category. In fact these further characteristics might even be understood as simply elaborating level rigidity, so closely connected to it are they. Consider novelty. Of course this term is extremely equivocal, but one gets some enhanced idea of the nature of emergent properties when one understands that they might, in some way, be rather novel. For example, perhaps they are *qualitatively* extremely different, or perhaps they are even *nomologically* different. Now, whether this latter condition can be fulfilled at all will depend on one's view regarding laws, what they are and how they function. If one takes it that the laws we derive from or theoretical and practical scientific pursuits are Humean like inductive abstractions, useful for predication but without essential claim to reality, then the idea of different laws functioning at different levels of complexity is not necessarily problematic. Of course the question will arise as to which laws, or which levels, we might rightly or wrongly take to be more fundamental – usually it is those governing the objects we take to more fundamental, namely particles and their constituents – but whatever answer we give to this question can be reconciled with the important context-relative claim that some property or other is weakly emergent. It may well be that said qualitative and nomological difference can eventually be reduced to similarity, just as it may be that novelty is fleeting. But the fact remains that it will be useful for the explanation of phenomena – and the other burdens of the scientist – to nevertheless utilise such in theory reducible properties. This essentially epistemic status is what aligns these criteria to the instantiations of emergence we will explore in the next two sections.

But before we move onto these positive sections a note more on the negative side must be made. For reasons which are not entirely clear ‘emergence’ has become a buzz word in biology and the other special sciences, with the vocabulary of emergence appearing in the titles of many scientific papers; however, in some cases it is not obvious that any substantive notion of emergence is actually being invoked. This may be entirely innocent: talk of emergent properties does seem to successfully conjure the highly complex nature of biological phenomena and the sophisticated technological methods involved in their investigation. Moreover, given our definitions of weak emergence it is likely that many (or even most) biological phenomena are weakly emergent. If so, then it is probably uncontroversial for a biologist to report his findings as the discovery of emergent properties. And scientists need not be criticised if they fail to offer a clear definition of emergence: there is a good case for a division of labour here, and defining emergence seems to me to be principally a task for the philosopher. But then it is not always clear what *scientific* function uses of emergence vocabulary can have in scientific articles. This is an important problem and much could be said about the role of emergence in the articles discussed above. Sometimes, however, it may be that a cynical explanation is more appropriate: one might venture the opinion that some scientists employ emergence vocabulary in research proposals, funding applications, and the titles of articles, just because this vocabulary is known to be currently in vogue and to possess an air of progress and technicality (and therefore likely to court favour in terms of funding and publication.) If this explanation has any plausibility then one should not seek to interpret all uses of emergence vocabulary as instantiations of our (or any other) characterisation of weak emergence.

4. The Game of Life and Weak Emergence

4.1 The Game Itself

There are many ways to study the phenomenon of complexity. After all, the concept of complexity is an extremely general and protean one that is widely manifested in many aspects of the real world, from the most fundamental of physical systems to large-scale biological ones. Unsurprisingly, then, the theories and attendant models we develop to talk about, explain, predict, understand and interact with (etc.) this real world can also themselves exhibit such complexity. It is these two closely connected and essential features of such models – that they are used to study complexity as it arises in the real world precisely in virtue of the fact that they themselves exhibit complexity in ways more amenable to analysis – that make them useful if we want to understand how the concept of (weak) emergence is utilised in systems biology, for without complexity there is no emergence. Many such models require a very high level of technical knowledge in order even to begin to understand how they work and what they imply. However, for our purposes it will suffice to present and relate just one of the most exquisitely simple examples of this broad kind of model – one that requires no mathematical expertise to understand, at least on a basic level, and yet one that displays perfectly many of the central features of emergent phenomena as they arise and are talked about in systems biology.

The so-called ‘Game of Life’, developed in 1970 by John Conway, a Cambridge mathematician, is the most famous example of a cellular automaton. Roughly, a cellular automaton is a model whose universe consists of a uniform grid that is both spatially and temporally extended and where both space and time are discrete. The grid is made up of **CELLS**, each of which is in a particular **STATE** at any given moment in time, t_n. The particular state of any given cell at t_n fully determines what non-relational properties that cell has at t_n. There are a finite number of possible states that any cell can be in, but since the state of a cell at t_n fully determines its non-relational properties at t_n, each cell can only be in a single state at t_n. What state a cell is in at t_n is fully determined by the various states of a finite set of cells at

t_{n-1}. Call this finite set of determining cells the cell's **NEIGHBOURHOOD** (a cell's neighbourhood can include the cell itself but in the case we explicate below it does not, and this is the norm). The neighbourhood of a particular cell is relative to that cell and is constant through time. The model as a whole is governed by a uniform dynamic such that at t_n an update **RULE** – one that will invoke the states of a cell's neighbouring cells at t_n – is applied to each and every cell in the universe. The application of this rule fully determines what state that cell will be in at time t_{n+1} (and thus what non-relational properties it will have at this time).

Before the peculiarities of the Game of Life are explained, the first thing to note is that cellular automata, as their very name indicates, are always closed systems. Moreover, they are usually fully deterministic systems, and although cellular automata have been developed in which, for example, the application of the update rule is statistically governed, we will not be concerned with such cases. So in general, what (macro-level) configurations of cells any particular instantiation of the model will manifest is, uncontroversially, fully determined by the (micro-level) states of cells in that model, and whatever states and configurations a model finds itself exhibiting at t_n are, again uncontroversially, fully determined by the states and configurations of that model in collusion with the application of the update rule at times $t_{0,}$ t_1, t_2 … t_{n-1}. We will return to this.

Now, as we have said, the Game of Life is a remarkably simple example of a cellular automaton. Its peculiarities are as follows:

> The **UNIVERSE** and its **CELLS** in the Game of Life: the grid that constitutes the universe is rectilinear so that each cell is a square with 2 spatial dimensions and 1 temporal dimension. The Universe in the Game of Life is infinite, both spatially and temporally.
>
> The possible **STATES** a cell might be in in the Game of Life: each cell is in one of two possible states, alive and dead.
>
> The set of cells that constitutes any particular cell's **NEIGHBOURHOOD** in the Game of Life: the neighbourhood of a cell consists of the 8 cells immediately surrounding it, above and below, to each side, and at the four corners.

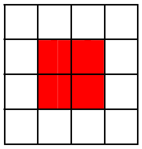
> The **RULE** that one applies to each and every cell in the universe at t_n in order to determine the state of each and every cell in the universe at t_{n+1} in the Game of Life: a cell which is dead at time t_n becomes alive at t_{n+1} iff exactly 3 of its neighbours were alive at t_n, and a cell which is alive at t_n dies at t_{n+1} iff fewer than 2 or more than 3 of its neighbours were alive at t_n. (There are lots of equivalent ways to state this rule. For example in terms of necessary conditions for survival, where death is defined derivatively as a failure to meet these conditions.)

Remember that the particular configuration of live and dead cells that is displayed by the universe at any given time is fully determined by (is a function of) the initial (t_0) configuration of that universe and the iterated application of the rule. Whatever configuration a universe displays at, say, t_{100} depends entirely upon – is entirely determined by – the rule and the configuration the universe displays at t_0.

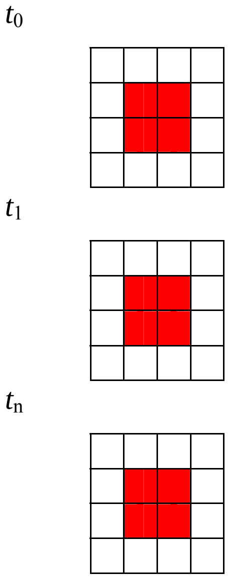
4.2 Prediction in the Game of Life

Sometimes it is easy to predict what configuration a particular universe will display at t_{100} from the configuration it displays at t_0. This is the case if we take a universe that consists entirely of dead cells except for a single so-called 'still life'. A still-life is a set of cells whose distribution of live and dead cells does not change with time. For example, take a universe whose initial configuration is such that all cells are dead except for 4 live cells arranged in a square 2-by-2 block (see below; there are lots of other still-lifes, but the block is the smallest, the simplest, and the most common – it will arise at some point in almost all games with medium to large initial configurations). In this case each of the four *live* cells in the universe will have each of the other 3 live cells in the universe as its neighbour alongside 5 dead cells. Thus none of the live cells will die (either from loneliness or overcrowding). Nor, however, will any new cells be born (no dead cells will become alive), since any given *dead* cell in the universe will have among its neighbours a maximum of 2 live cells, and this is not enough for producing life according to the update rule (it is said that there are not enough cells for reproduction to take place). The life-line of this particular universe – the configurations of this universe from t_0 to t_n – is rather dull since it does not change from moment to moment at all (see below). And the same is true of any universe (of which there are an infinite number) that consists solely of still-lifes suitably spaced.

A Block:

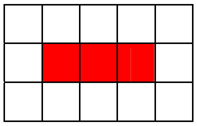


The Life-Line of a Block:



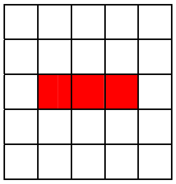
Only slightly less dull is the life-line of a universe that consists entirely of dead cells except for a single so-called ‘blinker’. A blinker is a set of cells that oscillates between one distribution and another and back again with a certain phase-rate (the phase-rate of a blinker is just the number of moments in time between identical distributions). For example, take a universe whose initial configuration is such that all cells are dead except for 3 live cells arranged in a 1-by-3 horizontal row (see below). This distribution of cells is a blinker with a phase-rate of two – if the row is horizontal at t_n then it will be vertical at t_{n+1} and back to horizontal at t_{n+2} The life line of such a universe is similarly predictable to the one described immediately above, except that whether *n* is odd or even must be taken into account, and of course the same is again true regarding all the life-lines of universes that consist of multiple blinkers suitably spaced, or indeed those that consists of some mixture of still-lifes and blinkers suitably spaced.

A Very Common 2-Phase Blinker:

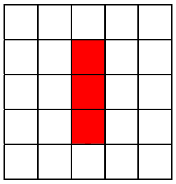


The Life-Line of this Blinker:

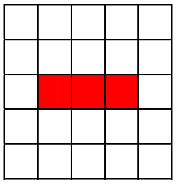
t_0



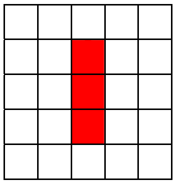
t_1



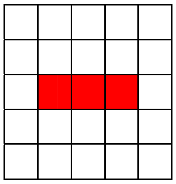
t_2



$t_{(\text{an odd number})}$

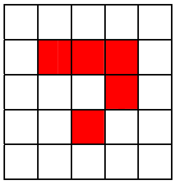


$t_{\text{(an even number)}}$



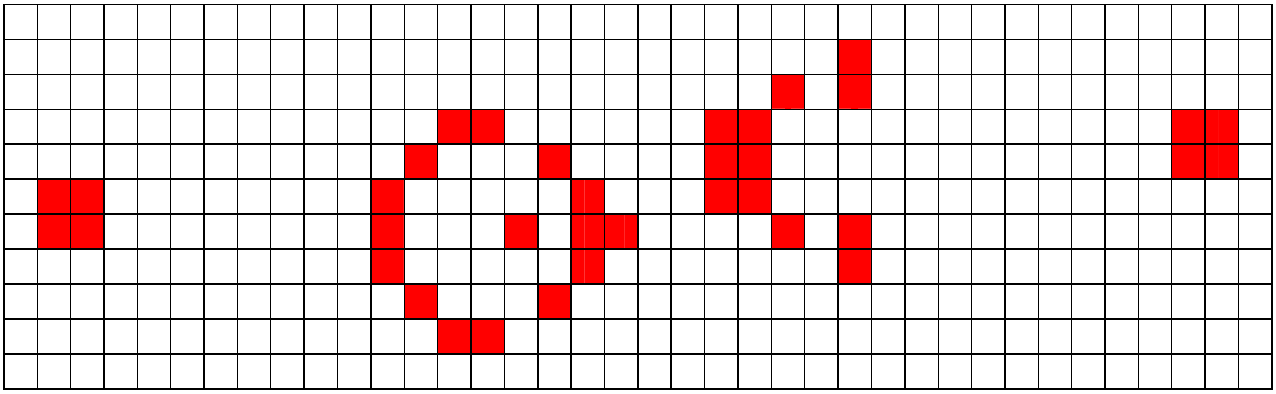
There are, however, certain life-lines, and more specifically certain cell-distributions, that are extremely interesting. For reasons that will become clear, perhaps the most important example of an extremely interesting (but nevertheless entirely predictable when observed in isolation) distribution of cells is the so-called ‘glider’ (see below). A glider has a phase rate of 4, but although after 4 moments of time have elapsed the shape of the live cells is once again identical with the initial shape, by this time the whole thing has moved diagonally by one cell in a direction determined by the compass orientation of the initial shape. When time moves slowly this distribution of cells appears to waddle across the universe, but when things are speeded-up it appears to *glide* into the distance indefinitely (supposing there is nothing for it to collide with), hence its name.

A Glider:



One reason the glider is such an interesting distribution of cells is because it is involved in many of the most interesting life-lines exhibited in the game of life. For example, there is a set of initial configurations called ‘glider guns’ (the first to be discovered, and still the most simple one known is that developed by Gosper, see below). Glider guns continuously emit gliders that move off into the infinite distance. Thus a universe that consists solely of a glider gun (or, yet again, glider guns suitably spaced) will have an infinitely growing population of live cells. Whether there were such initial configurations – ones that grew indefiniately – was the subject of a £50 bet set by Conway himself.

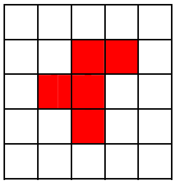
The Gosper Gun:



Or, to take a much more complex example, glider guns can be cunningly arranged with so-called ‘eaters’ and ‘bouncers’. Eaters destroy any glider that comes into contact with them at the correct angle. Bouncers refract – at varying degrees depending on the particular bouncer and angle of impact – any gliders that they come into contact with. In this way logic gates – AND, OR, NOT etc. – can be emulated, and indeed so can a fully functioning universal Turing machine! Extremely complex initial configurations have even been developed such that after a certain period of time they grow into a universal Turing machine, which after a certain period of time destroys itself after laying the foundations for another machine to grow, and so on. Clearly the prospects for interesting life-lines are extremely promising, a fact which is all the more remarkable when one takes into account the sheer (many say beautiful) simplicity of the model.

Now, the reason for mentioning some of these interesting life-lines is to introduce the intuitively strange fact that the development of certain life configurations, even some that are much more simple than those required to emulate a universal Turing machine, can be highly unpredictable (given our current best methods of prediction). A famous example is the so-called ‘R-pentomino’ (Conway called it the ‘F-pentomino’), which is a very simply initial configuration consisting of merely 5 live cells (see below).

The R-Pentomino:



Intuitively it seems that with such a simple initial configuration in such a simple model we should easily be able to predict all the properties its life-line would manifest at any particular time. But in fact this is not the case. Given our current best methods of calculation there is simply no way to predict whether the life-line will exhibit certain notable features except by simulation – that is, by performing each and every iteration of the update rule until we have reached the point in time wish to analyse. Two examples will be useful.

4.3 Two Examples of Weak Emergence in the Game of Life

So, our initial configuration is the R-pentomino, and let us suppose that we wish to know whether the life-line of this initial configuration manifests at any point either of the following two properties (taken from Bedau (1997)):

> Define a (macrostatic) property *G* such that an initial (t_0) configuration of cells in a standard life universe has *G* iff it produces at least one infinitely surviving glider within 150 moments.
>
> Define a (macrostatic) property *I* such that an initial (t_0) configuration of cells in a standard life universe has *I* iff its number of live cells grows indefinitely.

Short of simulation – that is, short of running the model by iterating the update rule the necessary number of times – there is just no way to know whether the R-pentomino has either *G* or *I*. As it happens, it does in fact have *G* but it does not have *I*. And of course for reasons that were given in the last section, although we can now know this – supposing we have performed the simulation – this does not mean that *G* and *I* cease to be emergent properties.

An emergent property is not surprising or unexpected or counterintuitive in the sense that such a property will cease to produce the psychological effect of ‘being surprised’ (etc.) after so many occurrences, but rather in the sense that such a property is surprising or unexpected or counterintuitive *given what we know about the initial configuration and the update rule*, and precisely *not given past experiences*. We might run simulations of many different initial configurations and discover that, say, 80 percent of the time *G* is instantiated. In which case, that *G* will be instantiated would be a feature of game of life life-lines that it would be reasonable to predict. And we might even go so far as to form a Humean-type inductive law such that it is stated that the probability of some initial configuration *X* having *G* is 0.8 (symbolised and generalised thus: P(X has F) = K). But none of this precludes *G* from being an emergent property.

Note that this highlights excellently the epistemological status of weak emergence, for whilst *for all we know*, there is no calculation or short cut to discovering whether some given initial configuration instantiates *G* or not, it has not been *proven* that this *must* be the case, and it may very well be that we (humans) are simply not yet good enough at or knowledgeable enough about mathematics to perform such a calculation or invent such a short cut. Moreover, it is easy to see how certain properties that can be ascribed to configurations are necessarily macrostatic properties. For example, the property of being able to spawn gliders is not a property that is possibly instantiated by a single cell. Thus the game of life can exhibit what we have called level-rigidity, which is of course closely linked to qualitative difference. And finally, the example of law forming given above shows how nomological difference can also be inherent.

5. A Cluster Definition of Weak Emergence Applied to Modern Biology

The possibility of providing one (or perhaps many) definitions of weak emergence has been discussed above. An emergent state or property has generally been characterised as something which has some combination of properties from the following list:

- The result of multiple microstates interacting in a non-linear way
- Unexpected
- Unintuitive/counterintuitive
- Amenable to discovery only by some process of computer simulation or physical experimentation (hence its unpredictability)
- Qualitatively Different to any of the microstates which give rise to M
- Nomologically Different to any of the microstates which give rise to M
- Level specific

The material which follows is intended to show that many of these characteristics are strongly analogous to those which scientists themselves (at least in the biological literature we have been studying) take to be the actual marks of emergence. Towards this end, the following scientific papers will be quoted from selectively:

Bhalla, U. S. and R. Iyengar (1999). "Emergent Properties of Networks of Biological Signaling Pathways." Science 283: 381-387.

Tabony, J. (2006). "Self-Organization and Other Emergent Properties in a Simple Biological System of Microtubules." ComPlexUs 3(4): 200-210.

Maini, P. K. (2004). "Using mathematical models to help understand biological pattern formation." C. R. Biologies 327(3): 225-234.

Shirakawa, T. and Y. P. Gunji (2007). "Emergence of morphological order in the network formation of Physarum polycephalum." Biophysical Chemistry 128(2-3): 253-260.

Efroni, S., D. Harel, et al. (2007). "Emergent dynamics of thymocyte development and lineage determination." Computational Biology 3(1): e13.

Fletcher, R. J. (2006). "Emergent Properties of Conspecific Attraction in Fragmented Landscapes." The American Naturalist 168(2): 207-219.

Reuter, H., F. Hölker, et al. (2005). "The concepts of emergent and collective properties in individual-based models—Summary and outlook of the Bornhöved case studies." Ecological Modelling 186(4): 489-501.

Mathieu, A., P. H. Cournede, et al. (2007). "Rhythms and Alternating Patterns in Plants as Emergent Properties of a Model of Interaction between Development and Functioning." Annals of Botany.

Eschenbach, C. (2005). "Emergent properties modelled with the functional structural tree growth model ALMIS: Computer experiments on resource gain and use." Ecological Modelling 186(4): 470-488.

There is not to be found in any of these papers a univocal definition of emergence, but there are numerous parallels between the concepts discussed in our account of emergence and the concepts employed across this body of scientific literature. This suggests that we have identified a family of concepts which could be usefully deployed in the analysis of particular instances of so-called emergence in biology.

5.1 Bhalla, Iyengar (1999), *Science*

This article, published in one of the most prestigious scientific journals, proposes a number of examples of emergent properties. The article’s abstract reads as follows:

> Page 381: ‘Many distinct signaling pathways allow the cell to receive, process, and respond to information. Often, components of different pathways interact, resulting in

> signaling networks. Biochemical signaling networks were constructed with experimentally obtained constants and analyzed by computational methods to understand their role in complex biological processes. These networks exhibit emergent properties such as integration of signals across multiple timescales, generation of distinct outputs depending on input strength, and duration and self-sustaining feedback loops. Feedback can result in bistable behavior with discrete steady-state activities, well-defined input thresholds for transition between states and prolonged signal output, and signal modulation in response to transient stimuli. These properties of signaling networks raise the possibility that information for "learned behavior" of biological systems may be stored within intracellular biochemical reactions that comprise signaling pathways.'

As with many scientific articles which prominently feature the vocabulary associated with emergence, no formal definition of the concept is provided. Nevertheless, a number of passages suggest that the authors are tacitly assuming a view of weak emergence as being associated with the characteristics we have identified. Consider the following passage:

> Page 381: 'Initially, signaling pathways were studied in a linear fashion, and it was shown that many important biological effects are obtained through linear information transfer. However, it has become increasingly clear that signaling pathways interact with one another and the final biological response is shaped by interaction between pathways. These interactions result in networks that are quite complex and may have properties that are non-intuitive… We developed models for simple networks… to determine if the network has properties that the individual pathways do not and if networking results in persistent activation of protein kinases after transient stimulus.'

It appears that Bhalla *et al* are concerned with properties which they take to result from complex interactions between multiple signalling pathways. The resulting properties are described as being often 'non-intuitive'. The precise meaning of this claim is not clear, but it seems reasonable to conclude that the authors take these properties to be somehow surprising or difficult to predict. This interpretation is reinforced by the fact that computer modelling is apparently required in order to discover the target properties. This of course is another characteristic which we have earlier identified as central to the notion of emergence. Further evidence that these concepts capture the notion of emergence employed by Bhalla *et al* comes from the following two passages:

> Page 382: 'Many signaling pathways are influenced by multiple stimuli, often acting synergistically'

> Page 386: 'The intricacy and variety of biological signaling networks often defy analyses based on intuition given the wealth of biochemical data a computational analysis is well-suited to handling both the complexity of multiple signaling interactions and the fine qualitative details'

What seems clear is that this article is concerned with properties which result from the non-linear interaction of multiple parameters, which are surprising or nonintuitive, and the discovery of which is (perhaps only) possible through some process of computer modelling (or physical experimentation). The article provides detailed examples of emergent properties, which I quote at some length:

> Page 386: 'Networking results in several emergent properties that the individual pathways do not have. These properties include the following: (i) Extended signal duration. The coupling of fast responses to the slow responses confers on the system the ability to regulate output for considerable periods after withdrawal of the initial signal. (ii) Activation of feedback loops. Feedback interactions occur commonly in biochemical processes. Many metabolic pathways are regulated by end-point feedback inhibition. Here, a positive feedback system involving PKC and MAPK was analyzed. This feedback loop has some noteworthy features. Sustained PKC activity results from initial activation of PKC by Ca21 and DAG and later activation due to synergy between AA and basal concentrations of DAG. AA concentrations are raised by the activation of cPLA2 by MAPK, which is stimulated indirectly by PKC. Thus, multiple modes (Ca21 and DAG and DAG and AA) of stimulating PKC are essential for the feedback loop. The magnitude and duration of the feedback loop are limited by the concentrations of the components of the system and other reactions that impinge on components of the feedback loop. The sequential phosphorylation reactions in the MAPK cascade are targets for regulation by protein phosphatases. MAPK is known to induce MKP, which is relatively specific for MAPK. In our model, MKP is effective in turning off the fully activated feedback loop under appropriate conditions.

> Additionally, down-regulation of PKC could also turn off the loop. Thus, both MKP and PKC levels could be determinants of CaMKII activity, connections not intuitively obvious in the absence of the network. (iii) Definition of threshold stimulation for biological effects. Signals of defined amplitude and duration are required to evoke a physiological response. Some of the parameters that define threshold stimulation can be ascertained from this analysis of signaling networks. From Fig. 2, D and E, it can be readily seen that signals of sufficient amplitude and duration are required such that the initial PKC activity rises above the second intersection point T so that the feedback loop becomes operational and sustained PKC and MAPK activity is obtained. Corresponding thresholds are seen in the inactivation process (Fig. 2, G and H). Thus, the system (that is, the network) defines what the threshold stimulation will be and which external stimuli would be capable of evoking a biological response. (iv) Multiple signal outputs. Multiple signal outputs from a network may provide a safety mechanism to ensure that only appropriate signals are translated into alterations in biological behavior. Such a safety mechanism could use hierarchical phosphorylations as a requirement for evoking a response. The multiple protein kinases required for hierarchical phosphorylation would ensure that the biological response is obtained only when the network is fully operational and all of the output protein kinases are functional.

5.2 Tabony (2006), *ComPlexUs*

In this article we again see many of the concepts which we take to be characteristic of emergence at work. Here is the article’s abstract:

> Page 200 (*whole abstract*): ‘In biological systems, emergent properties may develop due to numerous individual molecular elements in a population being strongly coupled in a non-linear manner. Under suitable conditions, the formation in vitro of a population of microtubules, a major component of the cellular skeleton (cytoskeleton), behaves as a complex system and develops a number of emergent phenomena. These preparations, which initially contain just two molecular species, a nucleotide and a protein, self-organize by reaction and diffusion and the morphology that develops is determined at a critical moment early in the process by weak external factors, such as

> gravity and magnetic fields. The process also results in other emergent phenomena, namely replication of form, generation of positional information, and collective transport and organization of colloidal-sized particles. Microtubules are responsible both for cellular organization and the transport of subcellular particles from one part of the cell to another. Frequently, this behaviour is triggered by some weak internal or external factor. The in vitro observations outlined thus illustrate how in a simple biological system, a complex behaviour may give rise to emergent phenomena that outwardly resemble major biological functions.'

The article begins by contrasting the concept of emergence with the notion of reductionism in biology:

> Page 200: 'Over the last 100 years, enormous advances in biology have been made based upon the general concept of molecular reductionism…The implication is that knowledge of the exact disposition of atoms in a molecule will eventually (if established for a sufficiently large number of proteins and other macromolecules) lead to a description of living systems…Molecular reductionism is, however, subject to limitations and most biologists realize that some biological properties or functions arise somehow simply because a large number of interacting molecular species are present. To anyone familiar with non-linear dynamics, this suggests that populations of biological molecules might behave as complex systems and develop emergent phenomena. Some scientists are asking whether some of the global properties of biological systems can be accounted for in terms of emergent properties and even whether life itself should be considered as such.'

> Page 201-202: 'This behaviour is not a result of the sum of the properties of individual microtubules and cannot be understood in terms of molecular reductionism. On the contrary, it arises from the collective action of the entire microtubule population in which individual microtubules interact and communicate with one another by way of the chemical trails that they themselves form. These observations illustrate how in a simple biological system, reactive processes give rise to a population of interacting elements, which behave as a complex system and show a number of emergent phenomena.'

The above passages confirm that, for Tabony, emergent properties may result from the non-linear interaction of multiple parameters. The suggestion that some biological properties cannot be 'reduced' to the underlying properties of more fundamental elements such as atoms should, I think, be interpreted as an epistemological – rather than an ontological – objection to reductionism about biology. The suggestion is just that our *knowledge* of certain biological properties cannot be reduced to knowledge of fundamental particles.

This article can also be seen as employing some of the other concepts which we take to be central to the concept of weak emergence: emergent properties are described as 'seemingly random' (p.202), i.e. surprising, non-intuitive, or difficult to predict; and computer simulation is employed (see especially pp. 207-209) in the discovery of what are taken to be emergent properties.

5.3 Maini (2003), *C.R.Biologies*

This paper presents:

> Page 225: 'some of the mathematical models that have been proposed to account for pattern formation in biology and consider[s] their implications… One of the most intriguing properties of many dynamical systems is their ability to spontaneously generate spatial and spatio-temporal patterns.'

The following passages indicate that Maini is concerned with biological properties which result from complex non-linear interactions, and which are best investigated through the use of mathematical modelling:

> Page 225: 'In developmental biology, a key aim is to understand the mechanisms underlying spatio-temporal pattern formation. Although genes play a crucial role, a study of genetics alone cannot provide a mechanistic understanding of how physical and chemical processes within a developing sytem conspire to produce the complex spatio-temporal cues to which cells respond and interact.'

> Page 226: Examples are discussed in which 'a number of complex mechanical and

> biochemical processes interact in a highly nonlinear way. Such systems are amenable to mathematical modelling and the role of the modeller is to suggest explanations, based on biologically plausible mechanisms, of observed behaviour and to make experimentally testable predictions.'

5.4 Shirakawa, Gunji (2007), *Biophysical Chemistry*

This article explicitly characterises emergent properties as arising from the interactions of multiple parameters. The abstract states:

> Page 253: 'Emergence in a system appears through the interaction of its components, giving rise to higher order or complexity in the system. We tested for the presence of emergent properties in a biological system using the simplest biological entity of a unicellular organism; the plasmodium of Physarum polycephalum, a giant unicellular amoeboid organism that forms a network-like tubular structure connecting its food sources. We let two plasmodium networks within a single cell interact with each other, and observed how the intracellular interaction affected the morphologenesis of the plasmodium networks. We found that the two networks developed homologous morphology. We further discuss the presence of autonomous and emergent properties in homologous network formation.'

Another passage reaffirms this key characteristic of emergence:

> Page 253: 'Emergence is a process of generation of complexity or higher levels of organization in a system from basic constituent parts. Emergence occurs through interaction of the system's components and has come to be widely regarded as a key concept in various scientific fields including nonlinear physics, complex systems science, systems theory and the study of artificial life. Emergence appears in any system showing orderly behavior, and in a broad sense involves generation of higher order that is irreducible to lower level description, though the meaning and usage of "emergence" depends on the context of each field.'

The second half of the above passage raises some further issues. Emergence is said to arise in any system showing orderly behaviour. This seems to me controversial, especially in the absence of an explicit definition of ‘order’. The passage also suggests that emergence is in tension with reductionism, although I think there is nothing in the article which implies an opposition to ontological reductionism; once again the epistemological reading is preferable. The following passage seems to confirm this in its assertion that ‘emergent behavior of a biological system can be directly derived from the functions of its components’. This passage also features the ‘unexpectedness’ hallmark of emergence, the ‘multiple parameters’ characteristic, and provides further examples of what the author takes to be emergent properties:

> Page 253-254: ‘Given some simple rules, automata produce complex patterns that would not be expected to emerge from a system governed by those rules… The notion of emergence can also be applied within a biological context. For example, swarm intelligence is frequently quoted as an emergent phenomenon. Both ants and bees show orderly behaviors in optimal path finding and nest construction…These could be considered to constitute emergent systems because higher order appears through the collection and interaction of their components… The hierarchical structure of a biological system has complexities in each layer and apparent emergent behavior of a biological system can be directly derived from the functions of its components. When we deal with a system in terms of emergence, we must therefore clarify the types of interaction that occur between the system’s elements and the kind of system structure or organization that gives rise to emergent phenomena. Thus, to investigate the emergent properties of a biological system, we began with experimental observation of emergent phenomena in the simplest biological entity, a unicellular organism’

Two further examples:

> Page 254: ‘[W]e attempted to establish an experimental system to observe emergent phenomena that appeared as a result of interactions in the cellular system. We let two plasmodium networks interact with each other and tested the effect of intracellular communication on network formation. We demonstrated that two connected networks form homologous networks homologous networks, thus implying an underlying emergent mechanism in the morphogenesis of *Physarum* plasmodium.’

> Page 259: ‘Homologous network formation is emergent in that the plasmodia autonomously generate morphological order through intracellular interaction between networks. However, to fully demonstrate the emergent aspect of the phenomenon, we must study the mechanism of homologous network formation in more detail.’

5.5 Efroni, Harel, Cohen (2007), *PLoS Computational Biology*

The usefulness of this article for the purposes of illustrating and defending our definition of weak emergence is its explicit emphasis on the role of computer modelling, and its account of a novel technology for this purpose:

> ‘Here, we use a computer-driven simulation that uses data about thymocyte development to generate an integrated dynamic representation—a novel technology we have termed reactive animation (RA). RA reveals emergent properties in complex dynamic biological systems.’
>
> ‘RA uses a bottom-up integration of diverse experimental data to create an integrated and dynamic representation of the system’s interacting cells and molecules… Here, we use RA to reveal unexpected emergent properties of thymocyte development.’

This article does not explicitly assert that an emergent property is always one that can only be discovered through some process of simulation (nor that all properties which can only be discovered in such a way are emergent), but the use of reactive animation to study emergent properties does suggest that the use of computer modelling is an important aspect of biologists’ understanding of the concept of emergence.

5.6 Fletcher Jr. (2006) *The American Naturalist*

The author of this article summarises his project as follows:

> Page 207: ‘Using individual-based simulations, I investigated the emergent properties of conspecific attraction during habitat selection on survival, fecundity, short-term

> fitness (survival#fecundity), and distributions in fragmented landscapes.’

In another passage the author reveals a conception of emergent properties as resulting from an interaction between multiple parameters. We can also see that computer modeling/simulation has been used to study these emergent properties:

> Page 208: ‘Emergent patterns resulting from conspecific attraction could be highly variable and depend on number of factors, including landscape structure (Lima and Zollner 1996), yet this potential has not been explored. I use an individual-based, spatially explicit simulation model to examine how conspecific attraction affects the survival, reproduction, and distribution of animals in a landscape context.’

The author of this article is aware that emergent phenomena can be difficult to predict. Here, however, the point is not simply that certain phenomena can only be predicted by making use of computer models, but that the models themselves are not completely reliable:

> Page 216: ‘While the model presented here provides a general assessment of the short-term effects of conspecific attraction in fragmented landscapes, it was not intended to simulate the behaviors of specific species (see Dumont and Hill 2001 for an example). Some model parameters would be difficult to estimate in the field, yet I chose this approach to allow full exploration of the potential behavior of conspecific attraction.’

> Page 216-217: ‘Results from the model suggest that conspecific attraction is one potential mechanism—previously unappreciated by conservation biologists and landscape ecologists—underlying the effects of patch size and habitat edge that have been observed across many taxa (e.g., Bender et al. 1998; Ries et al. 2004). Predicting the likelihood of these effects will depend on understanding the ultimate factors responsible for attraction and landscape context. While manipulating social cues to attract animals to suitable but unused areas has been suggested (Stamps 1988; Reed and Dobson 1993; Ward and Schlossberg 2004), the efficacy of such an approach remains relatively unknown, particularly in complex situations such as landscapes undergoing habitat loss and fragmentation. Nonetheless, results presented here suggest that conspecific attraction can have strong implications for habitat selection and that these effects can potentially be amplified with ongoing landscape change.’

Comments on the limitations of computer modeling are also to be found in some of the articles considered above: e.g. see Bhalla p. 386.

5.7 Reuter et al. (2005), *Ecological Modelling*

This article seems to prioritise the notion of 'levels' in order to characterise emergence:

> Page 489: 'In order to address different model characteristics we distinguish *collective* and *emergent* properties. Collective properties are those that are attributed equally to different organisation levels of the system. Emergent properties result from the activities of lower level entities on a higher organisation level, while not being present on the lower level. They can be subdivided into *aggregational* and *connective* properties. Emergent properties that are aggregational are those which emerge as a result of an aggregation procedure by an observer on the higher level which does not make sense or is not applicable on lower levels. Emergent properties that are connective, however, are based on an interaction network of lower level entities, which brings about the specific system characteristic.'

It is not easy to know what to say about this passage. The notion of level rigidity does seem to be an important aspect of our understanding of emergence, but it is not clear whether or not the sentence 'Emergent properties result from the activities of lower level entities on a higher organisation level, while not being present on the lower level' is intended as a precise definition of emergent properties. The proposed condition does not seem to be sufficient for emergence, because a table can have a weight of 10 kilos though none of its parts have the property 'weighing 10 kilos', while it is true that the weight of the table 'results from' the weights of its parts. Equally, the condition does not seem to be necessary for emergence: suppose we inject a small cloud of gas into a large sealed room. The cloud 'occupies' a certain position if and only if at least one of its constituent molecules is in that position. Then we can say that 'occupying position x' is a property instantiated by the cloud *and* by one of its molecules. The problem is that we may still wish to describe the position of the cloud as emergent: the 'area of occupancy' instantiated by the cloud is determined by the positions of its constituent molecules, but whether the cloud occupies a certain region may be an emergent phenomenon in the sense that it could not be easily predicted without a very sophisticated computer model. Reuter *et al* may be right that some kind of level rigidity is important for emergence, but nothing in the above quotation offers a robust characterisation of emergence. What is needed may be some notion of qualitative or nomological difference between levels.

5.8 Eschenbach (2005), *Ecological Modelling*

This article's use of 'emergence' is broadly in line with what we have encountered above. The notion of multiple parameters interacting and the importance of computer modeling are there clearly, and there is some awareness of the importance of level rigidity.

> Page 470: 'The functional structural tree growth model ALMIS uses the individual based modelling approach and is implemented in the object-oriented programming language SIMULA. All features (state variables) and functions (processes) are specified locally, on the level of the single plant organs. Increasing numbers of "copies" (objects) of these elementary units, Internodes, Leaves, Meristems, Roots, and Root tips, form the growing tree. Various procedures (e.g. Photosynthesis, Nutrient_uptake, Transport, Storage, Mobilisation, Respiration, Growth) are employed to describe carbon and nutrient uptake, and matter fluxes between the different plant organs. Combining plant physiology and architecture, ALMIS allows studying the effect of single ecophysiological and structural processes on whole tree growth and in the tree–environment system. Some of these effects, driven by microclimate, self-shading, variable nutrient availability, variable transport dynamics, and branching patterns are exemplified. From the interactions at the organ and sub-organ levels new features emerge at higher levels of plant organisation. These so-called emergent properties are, for example, lifetime spectrum of single organs, space filling ("architecture") and self-thinning of the crown. The most prominent emergent properties are the different growth forms of trees resulting from simulations under various conditions. Their causal interrelations are discussed in detail.'

5.9 Mathieu et al. (2007), *Annals of Botany*

This article is worth quoting briefly. It again illustrates the importance of computer simulations in order to predict the net results when multiple parameters interact in a way which is difficult to predict.

> Page 2:‘To model plasticity of plants in their environment, a new version of the functional–structural model GreenLab has been developed with full interactions between architecture and functioning. Emergent properties of this model were revealed by simulations, in particular the automatic generation of rhythms in plant development. Such behaviour can be observed in natural phenomena such as the appearance of fruit (cucumber or capsicum plants, for example) or branch formation in trees.’

Appendix A: Bibliographies

A.i Complete

Abbott, R. (2006). "Emergence explained: Abstractions: Getting epiphenomena to do real work." Complexity 12(1): 13-26.

Ablowitz, R. (1939). "The Theory of Emergence." Philosophy of Science 6(1): 1-16.

Alberghina, L. and H. V. Westerhoff, Eds. (2005). Systems Biology: Definitions and Perspectives. Berlin, Springer.

Alberghina, L. and H. V. Westerhoff (2005). Systems Biology: Did we know it all along? Systems Biology: Definitions and Perspectives. L. Alberghina and H. V. Westerhoff. Berlin, Springer.

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A.ii Key Papers and Sources

Complexity, published six times a year by Wiley, is a journal with a strong emphasis on both philosophical and scientific articles concerning emergence specifically, but also complexity more generally. It is an excellent resource for those who wish to pursue the theme of this project further. The quality is not always good, but some important and useful papers can be found by the discerning reader (most of which have been included in one or other of the sections in this appendix). Full contents can be found at: http://www3.interscience.wiley.com/journal/38804/home?CRETRY=1&SRETRY=0

Emergence, published three or four times each year by Erlbaum, will also be useful, as its name suggests! It is what we might call a 'concept' journal, in that it is not field-specific, but rather articles are selected precisely in virtue of the fact that they deal with the concept of emergence. This resource is particularly useful for examples of how the concept of emergence is at work in academic and even vocational areas other than philosophy and systems biology. Once again however, one be discerning as regards quality. Full contents can be found at: http://web.ebscohost.com/ehost/detail?vid=1&hid=7&sid=924ce583-2061-4d16-b414-d4e8635b495f%40sessionmgr9&bdata=JnNpdGU9ZWhvc3QtbGl2ZQ%3d%3d#db=bth&jid=7LT

The following two papers are both excellent introductions to the topic as it is discussed in the philosophical literature:

Bedau, M. A. (1997). "Weak Emergence." Nous **31**(Supplement: Philosophical Perspectives, 11, Mind, Causation, and World): 375-399.

> *Abstract*: An innocent form of emergence—what I call "weak emergence"—is now a commonplace in a thriving interdisciplinary nexus of scientific activity—sometimes called the "sciences of complexity"—that include connectionist modelling, non-linear dynamics (popularly known as "chaos" theory), and artificial life.1 After defining it, illustrating it in two contexts, and reviewing the available evidence, I conclude that the scientific and philosophical prospects for weak emergence are bright.

Chalmers, D., J. (2002). Strong and Weak Emergence. The Re-Emergence of Emergence: The Emergentist Hypothesis from Science to Religion. P. Clayton and P. Davies. Oxford, Oxford University Press**:** 244-254.

Abstract: The term 'emergence' often causes confusion in science and philosophy, as it is used to express at least two quite different concepts. We can label these concepts 'strong emergence' and 'weak emergence'. Both of these concepts are important, but it is vital to keep them separate.

(And although it contains much material that is not directly related to this project, the following online database, compiled by Chalmers, is an excellent resource for its thoroughness and accessibility: Mind Papers: a Bibliography of the Philosophy of Mind and the Science of Consciousness, from http://consc.net/mindpapers/

A.iii Selected Biological Literature (with abstracts where available)

Bhalla, U. S. and R. Iyengar (1999). "Emergent Properties of Networks of Biological Signaling Pathways." Science 283: 381-387.

Cokol, M., I. Iossifov, et al. (2005). "Emergent behavior of growing knowledge about molecular interactions." Computational Biology 23: 1243-1247.

Abstract: A billion nonredundant molecular interactions lie buried in the biomedical literature. A text-mining approach could help scientists better exploit this knowledge.

Efroni, S., D. Harel, et al. (2007). "Emergent dynamics of thymocyte development and lineage determination." Computational Biology 3(1): e13.

Abstract: Experiments have generated a plethora of data about the genes, molecules, and cells involved in thymocyte development. Here, we use a computer-driven simulation that uses data about thymocyte development to generate an integrated dynamic representation—a novel technology we have termed reactive animation (RA). RA reveals emergent properties in complex dynamic biological systems. We apply RA to thymocyte development by reproducing and extending the effects of known gene knockouts: CXCR4 and

CCR9. RA simulation revealed a previously unidentified role of thymocyte competition for major histocompatability complex presentation. We now report that such competition is required for normal anatomical compartmentalization, can influence the rate of thymocyte velocities within chemokine gradients, and can account for the disproportion between single-positive CD4 and CD8 lineages developing from double-positive precursors.

Eschenbach, C. (2005). "Emergent properties modelled with the functional structural tree growth model ALMIS: Computer experiments on resource gain and use." Ecological Modelling 186(4): 470-488.

Fletcher, R. J. (2006). "Emergent Properties of Conspecific Attraction in Fragmented Landscapes." The American Naturalist 168(2): 207-219.

Abstract: Attraction to conspecifics may have wide-ranging implications for habitat selection and metapopulation theory, yet little is known about the process of attraction and its effects relative to other habitat selection strategies. Using individual-based simulations, I investigated the emergent properties of conspecific attraction during habitat selection on survival, fecundity, short-term fitness (survival#fecundity), and distributions in fragmented landscapes. I simulated conspecific attraction during searching and settlement decisions and compared attraction with random, habitat-based (searching for the presence of habitat), and habitat quality sampling strategies (searching for and settling in high-quality habitat). Conspecific attraction during searching or settlement decisions had different consequences for animals: attraction while searching increased survival by decreasing time spent in nonsuitable habitat, whereas attraction during settlement increased fecundity by aggregating animals in highquality habitats. Habitat-based sampling did not improve fitness over attraction, but directly sampling habitat quality resulted in the highest short-term fitness among strategies. These results suggest that attraction can improve fitness when animals cannot directly assess habitat quality. Interestingly, conspecific attraction influenced distributions by generating patch size effects and weak edge effects, highlighting that attraction is one potential, yet previously unappreciated, mechanism to explain the widespread patterns of animal sensitivity to habitat fragmentation.

Lahaye, E., T. Aubry, et al. (2007). "Does water activity rule P. mirabilis periodic swarming? II. Viscoelasticity and water balance during swarming." Biomacromolecules 8(4): 1228-1235.

Abstract: Following the analysis of the biochemical and functional properties of the P. mirabilis extra cellular matrix performed in the first part of this study, the viscoelasticity of an actively growing colony was investigated in relation to water activity. The results demonstrate that the P. mirabilis colony exhibits a marked viscoelastic character likely due to both cell rafts and exoproduct H-bond networks. Besides, the water loss by evaporation during migration has been measured, whereas the experimental determination of the water diffusion coefficient in agar has allowed us to estimate the net water influx at the agar/colony interface. These data drive us to propose that a periodic increase of the water activity at the colony's periphery, mainly due to the drastic surface to volume ratio increase associated with swarming, causes the periodic and synchronous cessation of migration through the dissociation of exoproduct networks, which in turn strongly alters the matrix viscoelasticity.

Lahaye, E., T. Aubry, et al. (2007). "Does water activity rule P. mirabilis periodic swarming? I. Biochemical and functional properties of the extracellular matrix." Biomacromolecules 8(4): 1218-1227.

Abstract: The dynamics of bacterial colonies is complex in nature because it correlates the behavior of numerous individual cells in space and time and is characterized by emergent properties such as virulence or antibiotics resistance. Because there is no clear-cut evidence that periodic swarming of P. mirabilis colonies is ruled by chemical triggers responsible for cell-to-cell signaling in most of the biofilms, we propose that the observed periodicity relies on the colony's global properties. Hence, the biochemical and functional properties of the extracellular matrix (ECM) of P. mirabilis colonies were investigated. A binary exopolysaccharide mixture (1 and 300 kDa), glycinebetaine, and a phenoglycolipid were identified. Rheology, calorimetry, and water sorption experiments performed on purified EPS bring evidence that these exoproducts exhibit marked viscoelasticity, which likely relies on large scale H bond

networks. Such behavior is discussed in terms of water activity because the mechanical ECM properties were found to depend on hydration

Maini, P. K. (2004). "Using mathematical models to help understand biological pattern formation." C. R. Biologies 327(3): 225-234.

Abstract: One of the characteristics of biological systems is their ability to produce and sustain spatial and spatio-temporal pattern. Elucidating the underlying mechanisms responsible for this phenomenon has been the goal of much experimental and theoretical research. This paper illustrates this area of research by presenting some of the mathematical models that have been proposed to account for pattern formation in biology and considering their implications.

Mathieu, A., P. H. Cournede, et al. (2007). "Rhythms and Alternating Patterns in Plants as Emergent Properties of a Model of Interaction between Development and Functioning." Annals of Botany.

Abstract: Background and Aims: To model plasticity of plants in their environment, a new version of the functional–structural model GreenLab has been developed with full interactions between architecture and functioning. Emergent properties of this model were revealed by simulations, in particular the automatic generation of rhythms in plant development. Such behaviour can be observed in natural phenomena such as the appearance of fruit (cucumber or capsicum plants, for example) or branch formation in trees. Methods: In the model, a single variable, the source–sink ratio controls different events in plant architecture. In particular, the number of fruits and branch formation are determined as increasing functions of this ratio. For some sets of well-chosen parameters of the model, the dynamical evolution of the ratio during plant growth generates rhythms. Key Results and Conclusions: Cyclic patterns in branch formation or fruit appearance emerge without being forced by the model. The model is based on the theory of discrete dynamical systems. The mathematical formalism helps us to explain rhythm generation and to control the behaviour of the system. Rhythms can appear during both the exponential and stabilized phases of growth, but the causes are different as shown by an analytical study of the system. Simulated plant behaviours are very close to those observed on real plants. With a small number of parameters, the model gives very interesting results from a qualitative point of view. It will soon be subjected to experimental data to estimate the model parameters.

Mizraji, E. (2004). "The emergence of dynamical complexity: An exploration using elementary cellular automata." Complexity 9(6): 33-42.

Abstract: This work concerns the interaction between two classical problems: the forecasting of the dynamical behaviors of elementary cellular automata (ECA) from its intrinsic mathematical laws and the conditions that determine the emergence of complex dynamics. To approach these problems, and inspired by the theory of reversible logical gates, we decompose the ECA laws in a "spectrum" of dyadic Boolean gates. Emergent properties due to interactions are captured generating another spectrum of logical gates. The combined analysis of both spectra shows the existence of characteristic bias in the distribution of Boolean gates for ECA belonging to different dynamical classes. These results suggest the existence of signatures capable to indicate the propensity to develop complex dynamics. Logical gates "exclusive-or" and "equivalence" are among these signatures of complexity. An important conclusion is that within ECA space, interactions are not capable to generate signatures of complexity in the case these signatures are absent in the intrinsic law of the automaton.

Posfai, G., G. Plunkett, et al. (2006). "Emergent Properties of Reduced-Genome Escherichia coli." Science 312(5776): 1044-1046.

Abstract: With the use of synthetic biology, we reduced the Escherichia coli K-12 genome by making planned, precise deletions. The multiple-deletion series (MDS) strains, with genome reductions up to 15%, were designed by identifying nonessential genes and sequences for elimination, including recombinogenic or mobile DNA and cryptic virulence genes, while preserving good growth profiles and protein production. Genome reduction also led to unanticipated beneficial properties: high electroporation efficiency and accurate propagation of recombinant genes and plasmids that were unstable in other strains. Eradication of stress-induced transposition evidently stabilized the MDS genomes and provided some of the new properties.

Renfrew, C. (2008). "Neuroscience, evolution and the sapient paradox: the factuality of value and of the sacred." Philos Trans R Soc Lond B Biol Sci.

Abstract: The human genome, and hence the human brain at birth, may not have changed greatly over the past 60000 years. Yet many of the major behavioural changes that we associate with most human societies are very much more recent, some appearing with the sedentary revolution of some 10000 years ago. Among these are activities implying the emergence of powerful concepts of value and of the sacred. What then are the neuronal mechanisms that may underlie these consistent, significant (and emergent) patterns of behaviour?

Reuter, H., F. Hölker, et al. (2005). "The concepts of emergent and collective properties in individual-based models—Summary and outlook of the Bornhöved case studies." Ecological Modelling 186(4): 489-501.

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Abstract: Emergence in a system appears through the interaction of its components, giving rise to higher order or complexity in the system. We tested for the presence of emergent properties in a biological system using the simplest biological entity of a unicellular organism; the plasmodium of Physarum polycephalum, a giant unicellular amoeboid organism that forms a network-like tubular structure connecting its food sources. We let two plasmodium networks within a single cell interact with each other, and observed how the intracellular interaction affected the morphologenesis of the plasmodium networks. We found that the two networks developed homologous morphology. We further discuss the presence of autonomous and emergent properties in homologous network formation.

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in a non-linear manner. Under suitable conditions, the formation in vitroof a population of microtubules, a major component of the cellular skeleton (cytoskeleton), behaves as a complex system and develops a number of emergent phenomena. These preparations, which initially contain just two molecular species, a nucleotide and a protein, self-organize by reaction and diffusion and the morphology that develops is determined at a critical moment early in the process by weak external factors, such as gravity and magnetic fields. The process also results in other emergent phenomena, namely replication of form, generation of positional information, and collective transport and organization of colloidal-sized particles. Microtubules are responsible both for cellular organization and the transport of subcellular particles from one part of the cell to another. Frequently, this behaviour is triggered by some weak internal or external factor. The in vitroobservations outlined thus illustrate how in a simple biological system, a complex behaviour may give rise to emergent phenomena that outwardly resemble major biological functions.

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A.vii Literature and Resources for the Game of Life

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A.viii Selected Examples of Emergence in Other Areas (with abstracts where available)

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Abstract: This paper addresses the possibility that economics in the 21st century may return to its earlier affinities with biology. However, despite the widespread use of the term ‘evolutionary economics’ since 1982, there is little common understanding of the underlying problems and divergences of approach. Biology does not present a single, accepted paradigm as biologists are not united on key questions such as reductionism, teleology and the role of mathematical

formalism. Accordingly, a return to the biological Mecca by economists is likely to involve quite varied approaches. Furthermore, key ontological and methodological issues are likely to be highlighted by such a return; namely, the issues of reductionism, emergent properties and novelty. In particular, given that novelty is a characteristic of genuinely evolutionary systems, questions are raised concerning the limits of mathematical formalism in evolutionary economics.

Noell, C. (2007). "A look into the nature of complex systems and beyond "Stonehenge" economics: coping with complexity or ignoring it in applied economics?" Agricultural Economics 37(2-3): 219-235.

Abstract: Real-world economic systems are complex in general but can be approximated by the "open systems" approach. Economic systems are very likely to possess the basic and advanced emergent properties (e.g., self-organized criticality, fractals, attractors) of general complex systems. The theory of "self-organized criticality" is proposed as a major source of dynamic equilibria and complexity in economic systems. This is exemplified in an analysis for self-organized criticality of Danish agricultural subsectors, indicated by power law distributions of the monetary production value for the time period from 1963 to 1999. Major conclusions from the empirical part are: (1) The sectors under investigation are obviously self-organizing and thus very likely to show a range of complex properties. (2) The characteristics of the power law distributions that were measured might contain further information about the state or graduation of self-organization in the sector. Varying empirical results for different agricultural sectors turned out to be consistent with the theory of self-organized criticality. (3) Fully self-organizing sectors might be economically the most efficient. Finally, empirical implications of the results are discussed. Complexity theory should be considered as a valuable supplement to the existing analytical toolbox.

Rosenboom, D. (1997). "Propositional Music: On Emergent Properties in Morphogenesis and the Evolution of Music: Part II: Imponderable Forms and Compositional Methods." Leonardo Music Journal 7: 35-39.

Abstract: In Part I of this article, "Essays, Propositions and Commentaries," published in Leonardo Volume 30, Number 4 (1997), a point of view about creative music making termed "propositional music" was described. This method of composing involves proposing models for whole musical realities emphasizing the dynamic emergence of forms through evolution and transformation. Related areas of music, science and philosophy influencing this view were discussed. In Part II, this discussion is continued by considering the comprehension of initially undefined or imponderable forms, some premises with which to approach making propositional music and some fundamental steps to consider in constructing methods for composition and improvisation. The article concludes with comments on how substantive phenomena emerge and spread through complex dissipative and resonant processes and discussion of the relationship of propositional music to society.

Sawyer, R. K. (2001). "Emergence in Sociology: Contemporary Philosophy of Mind and Some Implications for Sociological Theory 1." American Journal of Sociology 107(3): 551-585.

Abstract: Many accounts of the micro-macro link use the philosophical notion of emergence to argue that collective phenomena are collaboratively created by individuals yet are not reducible to explanation in terms of individuals. However, emergence has also been invoked by methodological individualists; they accept the existence of emergent social properties yet claim that such properties can be reduced to explanations in terms of individuals and their relationships. Thus, contemporary sociological uses of emergence are contradictory and unstable. This article clarifies this situation by developing an account of emergence based in contemporary philosophy of mind. The philosophical account is used to evaluate contradictory sociological theories. Several unresolved issues facing theories of emergence in sociology are identified.

Sawyer, R. K. (2005). Social Emergence: Societies As Complex Systems. Cambridge, Cambridge University Press.

Schenk, K.-E. (2006). "Complexity of economic structures and emergent properties." Journal of Evolutionary Economics 16(3): 231-253.

Abstract: This concept revolves around differences of embeddedness of organizations in the macro patterns of routines (economic policy regimes), which in turn may differentially provide them–and the system as a whole–with 'procedural rationality' in dealing with identified problems in their relevant complex environment. Regularities of interdependence are specified between different regime patterns and the variety of coordination routines between and inside micro organizations. Corresponding regularities are also observed for internal governance routines of organizations, which in turn determine the behavioral adaptation by self-organization that may be rationally in a local perspective, but–contingent on the organization's embeddedness in the coordination structure–not necessarily so in a comprehensive one.

Smuts, B. (2006). Emergence in Social Evolution: A Great Ape Example. The Re-Emergence of Emergence: The Emergentist Hypothesis from Science to Religion. P. Clayton and P. Davies. Oxford, Oxford University Press**:** 166-186.

Appendix B: Glossary

Analytic/synthetic

Distinction between judgments or propositions by reference to the reason of their holding true. A judgment is analytic if the concept of its predicate is already contained in that of its subject; if the concepts of its subject and predicate are independent, it is synthetic. Alternatively, a proposition is analytic if it is true merely by virtue of the meaning of its terms or tautologous; otherwise, it is synthetic. For example:

"Bachelors are unmarried men." is analytic.

"Water freezes at 0°c." is synthetic.

Empiricists generally suppose that this distinction coincides with the a priori / a posteriori and necessary / contingent distinctions, while Kant held that synthetic a priori judgments are possible. Quine has argued that no strict distinction can be maintained, since the analyticity of any proposition can be denied, with suitable revisions of the entire system of language in which it is expressed.

A priori/A posteriori

Distinction between judgments by reference to the origin of our knowledge of them. A priori judgments are based upon reason alone, independently of all sensory experience, and therefore apply with strict universality. A posteriori judgments, on the other hand, must be grounded upon experience and are consequently limited and uncertain in their application to specific cases. Thus, this distinction also marks the difference traditionally noted in logic between necessary and contingent truths.

Cluster concept definition

A definition that does not consist in necessary and jointly sufficient conditions, but rather in explicating features of a term by means of several conditions, which may or may not be necessary for the term to apply, but which capture part of the meaning of the term. This kind of definition is used for terms that are used in a variety of contexts inside and outside science and are not explicitly introduced by means of necessary and sufficient conditions as part of a theory.

Definition

Definitions are means of preventing or eliminating differences in the use of languages. Definitions are explicit accounts of the meaning of a word or phrase that can be offered in different contexts and to different purposes. A lexical definition simply reports the way in which a term is already used within a language community – it is to capture actual usage. A stipulative definition freely assigns meaning to a completely new term, creating a usage that had never previously existed – it is to propose the adoption of shared use of a novel term. Combinations of lexical and stipulative elements are most common. Definitions can be given by means of providing necessary and jointly sufficient conditions for the use of a term. Often this is not possible (some people think it is only possible in the first place, when the term is introduced by means of a stipulative definition in the context of a scientific theory). In these cases, a cluster definition can be given (see cluster concept).

Deduction / induction

A distinction within logic between two kinds of reasoning, arguments, or inferences. In a deductive argument, the truth is preserved from the premises to the conclusion, i.e. necessarily, if the premises are true, then the conclusion is true. In an inductive argument, by contrast, the truth of the premises makes the truth of the conclusion merely probable.

Downward causation

Downward causation is the converse of some or other reductionist principle: the behaviour of the parts of a system (down) is determined by the behaviour of the whole system (up). That is, the whole is to some degree constrained by the parts (upward causation), but at the same time the parts are to some degree constrained by the whole (downward causation).

Epistemology

Epistemology is a branch of philosophy. It is the study of our method of acquiring knowledge and how our minds are related to reality, i.e. it gives answers to the question: “How/What do/can we know?”. It encompasses the nature of concepts, the constructing of concepts, the validity of the senses, logical reasoning, thoughts, memories, and emotions.

Induction

See Deduction/induction

Mereology

Mereology (from the Greek μερος, ‘part’) is the theory of parthood relations: of the relations of part to whole and the relations of part to part within a whole.

Metaphysics

Metaphysics is a branch of philosophy. It is the study of existence as such and answers the question “What exists?/What is the nature of things existing?”

Naturalism

Naturalism is an epistemological theory. It is the belief that all objects, events, and values can be wholly explained in terms of factual and/or causal claims about the world, without reference to supernatural powers or authority.

Necessary/sufficient

“Necessary” and “sufficient” are terms to characterize conditions for the application of a term, the use of a concept, or the occurrence of some phenomenon or event.

> A condition A is necessary for P, just in case: If A, then P.
>
> A condition A is sufficient for P, just in case: If P, then A.

Example:

> *being a mother* is a sufficient, but not a necessary condition for *being female*.
>
> *being female* is a necessary, but not a sufficient condition for *being a mother*.

Cockneys, according to the traditional definition, are all and only those born within the sound of the Bow Bells. Hence birth within the specified area is both a necessary and a sufficient condition for being a Cockney.

Ontology

Ontology is the branch of metaphysics that concerns the question what exists. It is often used interchangeably with metaphysics.

Physicalism

Physicalism is a metaphysical theory. It is the belief that all mental properties, states, and events can be wholly explained in terms of physical properties, states, and events.

Prediction

The explanation of an event that has not yet occurred by reference to observed regularities in the world. Predictions often rely on inductive reasoning (see Deduction/Induction).

Reduction

Reductionism captures a number of ontological, epistemological, and methodological claims about the relationships between different scientific domains. The basic question of reduction is whether the properties, concepts, explanations, or methods from one scientific domain (typically at higher levels of organization) can be deduced from or explained by the properties, concepts, explanations, or methods from another domain of science (typically one about lower levels of organization).

Substance

"Substance" is essentially a philosophical term of art. It denotes the underlying being that supports, exists independently of, and persists through time despite changes in the accidental features of whatever it is the substance of. The term goes back to Aristotle who identified substance as the most fundamental of the ten categories of being he distinguishes.

Sufficient

See Necessary/Sufficient

Supervenience

Supervenience is a concept characterising the relationship between two domains. A set of properties A supervenes upon another set B just in case no two things can differ with respect to A-properties without also differing with respect to their B-properties: “there cannot be an A-difference without a B-difference”.

Synthetic

See Analytic/synthetic

Appendix C: Open Problems and Future Work

Strong or ontological or metaphysical emergence faces the problem of being closely tied to the very problematic notion of downward causation. In order to salvage this kind of emergence, one would have to show either how it can do without downward causation, or how the problems facing downward causation may be solved. This is not something we have done here, nor are we confident it could be done. The most promising route would seem to lie in focussing on explanation, rather than on causation directly. If we can make a case for the *explanatory* independence of higher-order properties from lower-level properties, a convincing case for a weakened sense downward causation could still be made. That is, if we can show how the explanation of the obtaining of certain high-level properties in terms of other, high-level properties is illuminating in itself and adds to an explanation in terms of lower-level properties only, maybe there is a case for strong emergence without any strong downward causation.

In this case, however, the line between strong and weak emergence seems to blur rather. As we have seen, there is an entirely metaphysically innocent form of emergence being usefully put to work by scientists – useful precisely because of its explanatory power and methodological expediencies. Although at times the concept of weak emergence can seem rather uninteresting, due to its apparent utter ubiquity, there are also clearly times when it is useful and enlightening to class a property, phenomenon, or process as weakly emergent. This positive conclusion would only be enhanced by a proper exploration of certain other difficult concepts in systems biology that are very closely linked to that of emergence. Not only are these concepts in need of more rigorous definition and subsequent investigation for exactly the same reasons (outlined briefly right at the beginning of this project) that the concept of emergence was, but doing so will have a reciprocal effect.

As we have shown above, emergent properties are independent of, yet closely linked to more basic or less complex properties. Even if we do not go in for strong ontological emergence, even weak epistemological emergence assumes a picture according to which nature is composed of layers of complexity. The following concepts, all related to this basic picture, hence stand in the need of clarification:

- Levels
- Complexity
- Reduction
- Function
- Analyzability
- Purpose
- Modularity

Our philosophical analysis of and more general investigation into the concept of emergence has been a first and necessary step to better understanding the conceptual and ontological claims of systems biologists. However, more work in a similar vein must certainly be carried out.