

Difficult Concepts in Systems Biology: Emergence

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Motivation. System Biology is very much in the vogue, but is also reality in that full modelling of biological systems is now a possibility. The literature of systems biology have elements that are very well defined, such as different forms of high throughput data, knowledge of biological structures and dynamical modelling. However, the literature is also dominated by concepts that can only be describes as elusive and in many contexts unnecessary. Such concepts are “Function”, “Emergence”, “Purpose”, “Modularity”, “Level”, “Reduction”, “Analyzability”, “Cause” and “Machine as metaphor in biology”. There are most likely others. These concepts are problematic since they are easily used by the majority of the bio-science community, but there are no consensus about their definition or even the necessity of these concepts. We will define a series of projects that hopefully will clarify these concepts. (Cautionary note: The literature on the topic is extensive and the articles often appear in philosophical journals. So the articles read, should be chosen with serious care to avoid being overwhelmed.)

Background. Approaching the concepts of emergence can be done in a at least two ways: Firstly, a priori through general concepts from epistemology and metascience. Secondly, through investigation of how the concept is used in the scientific literature. Some effort should be spent at both. The first allows the problem to be seen in its generality and the second is more specific and would probably appeal more to scientists.

The motivation for this project is that emergence is used with increased frequency, but is hard to define, but nonetheless has intuitive meaning to many researchers. Given the elusiveness of definitions, we will unashamedly propose definitions according to our own intuitive understanding.

Strong Emergence: We will define this via a small example. The example might not be entirely uncontentious, but hopefully explains the main point. Assume that we have a 3-component system that is spatially uniform and characterized by the concentration of the 3 components. At time t let this be $\mathbf{x}(t)$. Let the dynamics of \mathbf{x} obeys a differential equations with first order, second and third order linear components. If the full dynamics can be inferred from observations of the behaviour of pairs of components, then the system is **reconstructable** (Zwicky, 2004). This would be the case if there were no 3rd order terms. If the equation system for all 3 are change the second order coefficients in the presence of a third components, then it possesses strong emergence.

$$\frac{dx_i}{dt} = \sum_j a_{i,j} x_j + \sum_{j,k} a_{i,j,k} x_j x_k \quad \frac{dx_i}{dt} = \sum_j b_{i,j} x_j + \sum_{j,k} b_{i,j,k} x_j x_k + \sum_{j,k,l} a_{i,j,k,l} x_j x_k x_l$$

In this little cartoon, we have 3 components interacting. As pairs they obey the first equations, while as triple they obey the lower equations. In the relationship of the third component changes the relationship of the first 2 components.

A property of system is **irreducible**, if it cannot be defined with less information than a total description of the system. A classic example is k bits and the property that an even number of them is zero (Bar-Yam, 2004). This clearly cannot be known by partial knowledge.

Weak Emergence (WE) is defined as a property that cannot be present with less than k objects. Often the property is found “surprising” in that the property was not easily foreseeable.

The existence of strong emergence is doubtful, but could have major consequences if it did exist. There is nothing odious about weak emergence except that the defining property is rarely if ever given in advance. We will only care about weak emergence. Weak Emergence is defined as a property that cannot be present with less than k objects. Here we provide two different, but related definitions:

1. A system is build up by sequentially adding components – e.g. a network where nodes are added one by one, or a chemical solution where compounds are added one by one. The property is emergent if the property exists in the system of k components but not in the system of $k-1$ components. Trivially, properties that directly refer to the number k of components are emergent, e.g. connected network motifs involving k nodes, or the property of having k components. Turing patterns are examples of emergent properties ($k=2$) (Maini, 2004). Each of the components alone cannot describe the Turing pattern seen when both components are together.

2. A system consists of k components with no reference to how it is build or created. A property of the system is emergent if it cannot be described with knowledge of only $k-1$ components (marginal information). Examples of emergent properties include a system of k binary nodes taking values 0 or 1. Whether the sum of all nodes is odd or even cannot be told from $k-1$ components. This form of emergence seems relevant when the system cannot be decomposed into systems of fewer components. Whether Turing patterns are emergent properties depend on whether the concentration of one component (in a two component system) can be determined from the concentration of the other component alone. This form of emergence is also close to predicting properties from observation because we rarely are able to observe the whole system.

Standard examples of “emergent properties” are: Network behaviour, such oscillations, robustness, multi-stability and memory. These concepts can be defined precisely. Other examples are consciousness in the brain that clearly is harder to define. Qualities like temperature and colour also have the property that they only appear when the number of molecules are large, but is here not easy to define and it could here be useful to use a concept of degree for emergence or gradual emergence.

Project Goals

- Read key literature. This would include Kim, Maini, Bar-Yam, Bhalla & Iyengar from reference list. The reference list below is larger than necessary, but should be helpful in literature search.
- Find examples of emergent properties. Find and discuss specific examples of emergent properties and the size of the systems necessary to them to appear. This will imply independent critical literature search.
- Computational aspects of emergence. Formulate simple dynamical models and investigate the probability of the standard emergent properties. This could for instance be done by sampling linear dynamical systems (Hirsch et al., 2004) and ask what is the probability that a random dynamical system possesses stability, robustness, oscillations,....
- Automatic search for emergence. For WE we always search for one of a small set of specific properties. Is it possible to make a satisfactory definition of WE that would be interesting? The problem here is, that a “random” property on k objects almost always will be emergent. This will make the concept trivial. One the other hand the specific emergent properties are quite simple and for instance calling Turing patterns emergent adds nothing to understanding.
- Is the concept of emergence necessary and useful?

Comments: i. Although most the interest in mergence comes from philosophers, it is our view that in systems biology is crucial to define it exactly in well defined dynamical systems. Ii. Possibility for collaborative projects: Emergence is only one of several difficult concepts. If several students were interested, we would only be happy to write projects on “Levels and Reductions” and “Function and Purpose” now.

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