

Group Report: Emergent Properties of Natural and Artificial Systems*

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Emergence, Pattern Formation, Self-Organization, Pre-Determinism

On the Meanings of Emergence

Emergence recently has become a popular term in some fields of science as well as in philosophy. Historically, it had already been widely used in the field of evolutionary theory and in what is now called philosophy of mind. In ordinary language *to emerge* simply means *to become known or apparent or to arise from certain conditions*. However, as *emergence* is slowly turning into a technical term, its meaning should be made explicit in order to be clear what one means. Particularly we wanted to take a look at the actual usage and the possible role of the notion of emergence in science. We chose to restrict ourselves to the mostly shared fields of competence the coauthors represent, i.e. electrophysiological single cell recording in cats and monkeys, mathematical modelling of pattern formation in connection with neural activity and developmental neurobiology.

It is helpful to distinguish between two levels of inquiry. They can be characterized by two questions. On the epistemological level we ask: What do we know about the world? For example: Do we know what activity a neuron in area V1 has when a monkey looks at a moving bar? Or: Can we infer (predict) neural activity in the cortex of a monkey engaged in a memory task when we

have a model of synaptic connectivity and some knowledge of boundary conditions? On the ontological level we ask: What is the case? For example, we are convinced that it is the case that there always is some specific neural activity going on during any mental operation although we might not know which. This distinction is important because some researchers use the term emergence merely to describe cases in which something appears unknown or unexpected to them.

In philosophy of science, emergence is used in the ontological domain, i.e. it refers to the objective properties of systems themselves and not to our knowledge of them. A property of a system is called weakly emergent, if it is not a property of a component but is determined by the properties, arrangement, and interactions of the components of the system. Strong emergence is weak emergence plus the thesis that those system properties cannot fully be explanatorily reduced to the properties, arrangement, and interactions of the system's components.

There is a second distinction in the time domain. Weak and strong emergence as explained can be called synchronic as they refer to systems in which component and system properties exist in the same time span. If a property emerges in time we call this diachronic emergence. Notice, that the problem of explanation and reduction is primarily a problem of synchronic emergence whereas diachronic emergence is more closely related to the ordinary language view of *appearing*.

In our discussions we concluded that from a scientific view we cannot accept the notion of "strong emergence" in the neural and behavioural or cognitive domains since it would imply an a priori irreducibility of macroscopic phenomena such as

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the EEG. We decided to adopt a view in which the formation of patterns is the problem around which aspects of emergence can be accessed.

Pattern Formation in Models of Neural Activity

Neural networks are often conceived of primarily as sophisticated devices that transform input into output in manners that can be quite complex. From the early days of theoretical work in neural networks, however, the capacity of neural networks to generate patterns autonomously has been studied in appropriate mathematical models (Wilson and Cowan, 1973; Amari, 1977). In these models, connections within a network of neurons are sufficiently strong so as to stabilize patterns of activation even in the absence of sensory input. Mathematically, such networks go through instabilities as parameters such as the total amount of input are varied. These instabilities define the strongly cooperative limit case, in which these neural networks generate responses that are not entirely determined by input.

This property can be used to address the potential, or also real, ambiguity of visual sensory information. For instance, the perception of coherent apparent motion arises in response to stimuli that are potentially highly ambiguous, because motion can be seen between many different parts of the visual array if those parts are presented in isolation. This ambiguity can sometimes be realized in experience, when two or more perceptually distinct patterns arise from identical stimuli. The properties of such bistable percepts are compatible with those predicted from an account in terms of strongly cooperative neural networks (Hock *et al.*, 1993; Giese, 1997). In this account, all potential elementary motions are activated in a neural representation, but those realized in experience inhibit those not realized in experience to a degree. Under appropriate circumstances, this pattern of interaction leads to bistability: either of the competing elementary motions can be activated. If the stimulus is changed so as to favor one of the alternative organized patterns of motion, the differences in activation between perceived and unperceived elementary motions decreases. This leads to the prediction that adaptation, considered a measure of the degree of activation of a particular motion detector, depends on the per-

ceived motion pattern: more stable motion patterns are stronger adaptors. This turns out to be empirically true (Hock *et al.*, 1996). On the other hand, adaptation occurs to stimulated but unperceived elementary motions! Thus pattern level and elementary motion level are really one and the same.

Strong cooperativity thus leads to pattern formation in visual perception. This form of pattern formation is flexible, because continuously many different patterns can be generated as simulation changes. Thus, although motion percepts have regularity such as those captured by the Gestalt rules, which result from the pattern of interaction in the neural network, the network remains responsive to stimulation and in this sense is capable of processing information. This form of pattern formation might thus be considered emergent, because the pattern resulting is not uniquely determined by the current stimulus. Fluctuations, prior perceptual history, but also information from other layers of representation may contribute to the formation of an organized percept.

We also discussed a model for neural activities that demonstrates emergence of spatiotemporal patterns when the external noise level is increased. Each of its elements is subject to external noise. These elements (McCulloch-Pitts neurons) are isotropically arranged on a lattice and interact with a strength that depends exponentially on their pairwise Euclidian distance. This system displays large scale emergent spatio-temporal structures at very specific values of unspecific, external, stochastic parameters namely the amplitude of the stochastic fluctuations (spatiotemporal stochastic resonance). Several global, geometric parameters of the emergent patterns (mean curvature of spirals) can be observed to be correlated with the this microscopic parameter. Similarly the response to external stimuli (e.g. moving bar) is observed to be correlated to microscopic parameters for instance in a resonant response to the stimulus velocity (Mayer-Kress, 1998: this issue, pp. 677–685).

Pattern Formation in Cognition and Neural Functioning

A large body of evidence from neuropsychology, electrophysiology and neuroimaging indicates that cortical function, including working memory, is

mediated by distributed representations over many distinct subdivisions of the cortex containing cellular assemblies. Thus, neural coding is based on dynamic recruitment of neurons into dynamical functional groups. A certain object can then be thought of as being represented as a unique pattern of activated neural subnets and, thus, representing the response of the system to the corresponding stimulus in a distributed manner. Thereby so-called working memory and long-term memory seem to share the same neural substrate in the cerebral cortex. That substrate consists in a system of widespread, overlapping and interconnected networks of cortical neurons. Such configurations, which are hierarchically organized, can be regarded as patterns in the temporal as well as the spatial domain. Thus, pattern formation in complex systems seems to be appropriate as a conceptual frame for a theory of neuronal functioning. Within this framework, the formation of patterns is due to the internal dynamics of the entire system which is related to the architecture of the system (Fuster, 1998: this issue, pp. 670–676).

The Concept of Cell Assemblies

Cell assemblies constitute a unifying concept in theorizing on spatiotemporal patterns of neural activity. It has been suggested that groups of cells related to the same visual percept, memorandum (memory), or motor act may join with other neurons involved in the same process. Hebb (1949) originally proposed the existence of cell assemblies of simultaneously active neurons that are formed on the basis of the specificity of anatomical connections. Recently, it was proposed that these assemblies are more than just coactivated groups of neurons, because they share a certain label. Moreover, physiological evidence suggest that assemblies can be formed dynamically. Two candidate labels for assembly formation are synchrony of action potentials fired by different neurons, and co-modulations of firing rates. According to the first candidate mechanism, neurons that participate in a single assembly fire their action potentials at approximately the same time. According to the second mechanism, neurons that belong to a single assembly all exhibit an enhanced firing rate. In this way each individual neuron may join different groups according to the task

requirements. Although the usefulness of the concept is evident, it is not yet supported by unequivocal evidence, and a hot topic for debate among neuroscientists. Nonetheless, ongoing research in the visual modality (Roelfsema, 1998: this issue, pp. 691–715) and in sensorimotor integration (Vaadia, 1998: this issue, pp. 657–669) provides supportive evidence for the involvement of synchrony and rate modulations in the dynamic formation of cell assemblies.

The configurations of cell assemblies appear to be highly dynamic. Due to changes in the activation of the nervous system and also due to the plasticity of the system, as observed as the modification of interneuronal interactions, each cell can rapidly associate with a functional group and disassociate from it again. Such modulation of neuronal interactions allow each neuron to become a member of several different groups and participate in different computational tasks. The above notion is supported by experimental findings which indicate that the level of correlated activity between neurons can be modified on a short time scale, within the range of a basic cognitive process such as stimulus perception or preparation of a specific movement (Vaadia, 1998).

Emergence of Large Scale Oscillations in the EEG

On a microscopic level we have evidence for functionally related cell assemblies that can show synchronous activity on a large range of scales: From single columns including of the order of thousands of neurons to assemblies that dynamically recruit millions of neurons. The corresponding time-scales span ranges from milliseconds to tens of milliseconds (e.g. 40 Hz oscillations). Although it is evident that synchronous activity on a micro-level can generate a macroscopic electromagnetic signal (EEG/MEG) it is still a largely open problem how an observed EEG pattern (and their range of frequencies and voltage levels) can be reduced to the activity of neuronal cell assemblies. There exists, however, some evidence for a correlation of activity on both a cellassembly level as well as as an EEG/MEG level with stimuli and behavior. We can also expect that with learning we will find an increase in the number of cells involved in a certain assembly. In the context of this workshop the emergence of macroscopic electro-

magnetic brain signals can be considered to be of a relatively strong type. An interesting open problem is to establish closer connections between the spike patterns (attractors) recorded from cells and the complexity observed in the EEG/MEG as it varies as a function of the type of input. For example response to input of multiple modality could involve the activation of multiple assemblies which then could be reflected in a large range of changes in frequencies (Fuster, 1998: this issue, pp. 670–676; Mayer-Kress, 1998: this issue, pp. 677–685).

Setting the Stage

Basic structural features of neural networks are generated in the course of brain development under the instruction of the genes. These, in turn, are products of evolution. In its course, novel brain capabilities may have arisen, in part of the cases, as consequences of duplications and recombinations of genes or its parts, especially of its regulatory sections; though immediate phenotype effects are expected to be small, such events may have initiated distinct new directions of evolution. Generally, the fundamental role of developmental genetics for an understanding of brainfunctions should not be underestimated. Growing axons navigate using genetically determined qualitative and quantitative biochemical guidance cues to form appropriate connections. Internally generated activity-dependent processes lead to further specifications such as map sharpening, but initial and boundary conditions of such self-organisation are still under genetic control. This sets the stage for modifications by external inputs, including learning. The relative contribution of activity-dependent processes in the formation of the neural network is itself a result of evolutionary forces. Too much self-organization, despite its intellectual appeal, would reduce fitness because it would take too long to develop (Gierer and Müller, 1995; Gierer, 1998: this issue, pp. 716–722).

Concluding Remarks

Specific conclusions: the limitations of the pattern view

In our discussions we have re-interpreted the problem of emergence into the problem of how pattern are formed at multiple levels, under the

influence of the environment, flexibly and dynamically. We have discussed a small set of examples which were intended to stand paradigmatically for a larger ensemble of phenomena. Does this pattern view exhaust the domain of natural and artificial systems? This must remain an open question. Higher cognitive functions including, in particular language, are not reached by the pattern view in an obvious way.

Philosophical conclusion

As we could learn, the term emergence was used in our group in a more epistemological sense. People are constructing mathematical models or analyse their empirical data and suddenly they see patterns *emerging* in the sense of appearing in a unexpected or hitherto unknown form. This is an epistemological experience. But now comes the ontological part: As patterns display regularities and regularities might be a hint for lawfulness scientists now try to find those regularities or even laws (and use it for predictions). They try to explain how these patterns emerge out of the properties of the components of the systems, i.e. the (real or hypothetical) neurons, their arrangement, their properties and their interactions. Thus the scientific endeavour may be regarded as the attempt to show that there are no strongly emergent properties in the sense we introduced this term. So why should the concept of strong emergence be useful for science? Calling something strongly emergent does not explicate anything. But it describes something. It describes the opinion of someone who thinks that a certain system property or *emerging* property (in the weak or diachronic sense) is not fully explainable or reducible in principle. So it may be useful to claim that something is strongly emergent only in order to provoke scientists into explaining this property. Apparently, this is happening for the property of *conscious* right now: Although many thinkers are convinced that this property may never be explained because it is not directly observable (e.g. Stieve 1998: this issue, pp. 445–454), many empirical scientists have begun to approach this question not be conceptual arguments alone, but by doing empirical work to show that conscious properties can perhaps be explained after all. Moreover: even if one is convinced that consciousness is strongly

emergent one might attempt to falsify this view in order to find empirically based arguments as to why consciousness cannot be explained. There-

fore, one can be a methodological reductionist even if one thinks that reductionism is wrong at the ontological level.

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