Emergence

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For other uses see Emergence (disambiguation), Emergent, and Emergency.
See also the closely related articles: Spontaneous order and self-organization.

In philosophy, systems theory and the sciences, **emergence** is the way complex systems and patterns arise out of a multiplicity of relatively simple interactions. Emergence is central to the theories of integrative levels and of complex systems.

A termite "cathedral" mound produced by a termite colony: a classic example of emergence in nature.

Contents

Definitions

The concept has been in use since at least the time of Aristotle.[1] John Stuart Mill[2] and Julian Huxley[3] are just some of the historic luminaries who have written on the concept.

The term "emergent" was coined by the pioneer psychologist G. H. Lewes, who wrote:

> "Every resultant is either a sum or a difference of the co-operant forces; their sum, when their directions are the same -- their difference, when their directions are contrary. Further, every resultant is clearly traceable in its components, because these are homogeneous and commensurable. It is otherwise with emergents, when, instead of adding measurable motion to measurable motion, or things of one kind to other individuals of their kind, there is a co-operation of things of unlike kinds. The emergent is unlike its components insofar as these are incommensurable, and it cannot be reduced to their sum or their difference." (Lewes 1875, p. 412)(Blitz 1992)

Professor Jeffrey Goldstein in the School of Business at Adelphi University provides a current definition of emergence in the journal, *Emergence*.(Goldstein 1999). For Goldstein, emergence can be defined as: "the arising of novel and coherent structures, patterns and properties during the process of self-organization in complex systems."(Corning 2002)

Goldstein's definition can be further elaborated to describe the qualities of this definition in more detail:

> "The common characteristics are: (1) radical novelty (features not previously observed in systems); (2) coherence or correlation (meaning integrated wholes that maintain themselves over some period of time); (3) A global or macro "level" (i.e. there is some property of "wholeness"); (4) it is the product of a dynamical process (it evolves); and (5) it is "ostensive" - it can be perceived. For good measure, Goldstein throws in supervenience -- downward causation." (Corning 2002)

Strong vs. weak emergence

Emergence may be generally divided into two perspectives, that of "weak emergence" and "strong emergence". Weak emergence describes new properties arising in systems as a result of the interactions at an elemental level. Emergence, in this case, is merely part of the language, or model that is needed to describe a system's behaviour.

But if, on the other hand, systems can have qualities not directly traceable to the system's components, but rather to how those components interact, and one is willing to accept that a system supervenes on its components, then it is difficult to account for an emergent property's cause. These new qualities are irreducible to the system's constituent parts (Laughlin 2005). The whole is greater than the sum of its parts. This view of emergence is called strong emergence. Some fields in which strong emergence is more widely used include etiology, epistemology and ontology.

Regarding strong emergence, Mark A. Bedau observes:

> "Although strong emergence is logically possible, it is uncomfortably like magic. How does an irreducible but supervenient downward causal power arise, since by definition it cannot be due to the aggregation of the micro-level potentialities? Such causal powers would be quite unlike anything within our scientific ken. This not only indicates how they will discomfort reasonable forms of materialism. Their mysteriousness will only heighten the traditional worry that emergence entails illegitimately getting something from nothing."(Bedau 1997)

However, "the debate about whether or not the whole can be predicted from the properties of the parts misses the point. Wholes produce unique combined effects, but many of these effects may be co-determined by the context and the interactions between the whole and its environment(s)." (Corning 2002) Along that same thought, Arthur Koestler stated, "it is the synergistic effects produced by wholes that are the very cause of the evolution of complexity in nature" and used the metaphor of Janus to illustrate how the two perspectives (strong or holistic vs. weak or reductionistic) should be treated as perspectives, not exclusives, and should work together to address the issues of emergence.(Koestler 1969) Further,

> "The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe..The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. At each level of complexity entirely new properties appear. Psychology is not applied biology, nor is biology applied chemistry. We can now see that the whole becomes not merely more, but very different from the sum of its parts."(Anderson 1972)

Objective or subjective quality

The properties of complexity and organization of any system are considered by Crutchfield to be subjective qualities determined by the observer.

> "Defining structure and detecting the emergence of complexity in nature are inherently subjective, though essential, scientific activities. Despite the difficulties, these problems can be analysed in terms of how model-building observers infer from measurements the computational capabilities embedded in non-linear processes. An observer’s notion of what is ordered, what is random, and what is complex in its environment depends directly on its computational resources: the amount of raw measurement data, of memory, and of time available for estimation and inference. The discovery of structure in an environment depends more critically and subtly, though, on how those resources are organized. The descriptive power of the observer’s chosen (or implicit) computational model class, for example, can be an overwhelming determinant in finding regularity in data."(Crutchfield 1994)

On the other hand, Peter Corning argues "Must the synergies be perceived/observed in order to qualify as emergent effects, as some theorists claim? Most emphatically not. The synergies associated with emergence are real and measurable, even if nobody is there to observe them." (Corning 2002)

Emergence in philosophy

In philosophy, **emergence** is often understood to be a much stronger claim about the etiology of a system's properties. An emergent property of a system, in this context, is one that is not a property of any component of that system, but is still a feature of the system as a whole. Nicolai Hartmann, one of the first modern philosophers to write on emergence, termed this *categorial novum* (new category).

Emergent properties and processes

An **emergent behaviour** or **emergent property** can appear when a number of simple entities (agents) operate in an environment, forming more complex behaviours as a collective. If emergence happens over disparate size scales, then the reason is usually a causal relation across different scales. In other words there is often a form of top-down feedback in systems with emergent properties. The processes from which emergent properties result may occur in either the observed or observing system, and can commonly be identified by their patterns of accumulating change, most generally called 'growth'. Why emergent behaviours occur include: intricate causal relations across different scales and feedback, known as interconnectivity. The emergent property itself may be either very predictable or unpredictable and unprecedented, and represent a new level of the system's evolution. The complex behaviour or properties are not a property of any single such entity, nor can they easily be predicted or deduced from behaviour in the lower-level entities: they are irreducible. No physical property of an individual molecule of air would lead one to think that a large collection of them will transmit sound. The shape and behaviour of a flock of birds[1] or shoal of fish are also good examples.

One reason why emergent behaviour is hard to predict is that the number of interactions between components of a system increases combinatorially with the number of components, thus potentially allowing for many new and subtle types of behaviour to emerge. For example, the possible interactions between groups of molecules grows enormously with the number of molecules such that it is impossible for a computer to even count the number of arrangements for a system as small as 20 molecules.

On the other hand, merely having a large number of interactions is not enough by itself to guarantee emergent behaviour; many of the interactions may be negligible or irrelevant, or may cancel each other out. In some cases, a large number of interactions can in fact work against the emergence of interesting behaviour, by creating a lot of "noise" to drown out any emerging "signal"; the emergent behaviour may need to be temporarily isolated from other interactions before it reaches enough critical mass to be self-supporting. Thus it is not just the sheer number of connections between components which encourages emergence; it is also how these connections are organised. A hierarchical organisation is one example that can generate emergent behaviour (a bureaucracy may behave in a way quite different from that of the individual humans in that bureaucracy); but perhaps more interestingly, emergent behaviour can also arise from more decentralized organisational structures, such as a marketplace. In some cases, the system has to reach a combined threshold of diversity, organisation, and connectivity before emergent behaviour appears.

Unintended consequences and side effects are closely related to emergent properties. Luc Steels writes: *"A component has a particular functionality but this is not recognizable as a subfunction of the global functionality. Instead a component implements a behaviour whose side effect contributes to the global functionality [...] Each behaviour has a side effect and the sum of the side effects gives the desired functionality"* (Steels 1990). In other words, the global or macroscopic functionality of a system with "emergent functionality" is the sum of all "side effects", of all emergent properties and functionalities.

Systems with emergent properties or emergent structures may appear to defy entropic principles and the second law of thermodynamics, because they form and increase order despite the lack of command and central control. This is possible because open systems can extract information and order out of the environment.

Emergence helps to explain why the fallacy of division is a fallacy. According to an emergent perspective, intelligence *emerges* from the connections between neurons, and from this perspective it is not necessary to propose a "soul" to account for the fact that brains can be intelligent, even though the individual neurons of which they are made are not.

Emergent structures in nature

Emergent structures are patterns not created by a single event or rule. Nothing commands the system to form a pattern. Instead, the interaction of each part with its immediate surroundings causes a complex chain of processes leading to some order. One might conclude that emergent structures are more than the sum of their parts because the emergent order will not arise if the various parts are simply coexisting; the interaction of these parts is central. Emergent structures can be found in many natural phenomena, from the physical to the biological domain. For example, the shape of weather phenomena such as hurricanes are emergent structures.

It is useful to distinguish three forms of emergent structures. A **first-order** emergent structure occurs as a result of shape interactions (for example, hydrogen bonds in water molecules lead to surface tension). A **Second-order** emergent structure involves shape interactions played out sequentially over time (for example, changing atmospheric conditions as a snowflake falls to the ground build upon and alter its form). Finally, a **third-order** emergent structure is a consequence of shape, time, and heritable instructions. For example, an organism's genetic code sets boundary conditions on the interaction of biological systems in space and time.

Non-living, physical systems

In physics, emergence is used to describe a property, law, or phenomenon which occurs at macroscopic scales (in space or time) but not at microscopic scales, despite the fact that a macroscopic system can be viewed as a very large ensemble of microscopic systems.

An emergent property need not be more complicated than the underlying non-emergent properties which generate it. For instance, the laws of thermodynamics are remarkably simple, even if the laws which govern the interactions between component particles are complex. The term emergence in physics is thus used not to signify complexity, but rather to distinguish which laws and concepts apply to macroscopic scales, and which ones apply to microscopic scales.

Some examples include:

- Colour: Elementary particles have no colour; it is only when they are arranged in atoms that they absorb or emit specific wavelengths of light and can thus be said to have a colour.
- Friction: Forces between elementary particles are conservative. However, friction emerges when considering more complex structures of matter, whose surfaces can convert mechanical energy into heat energy when rubbed against each other. Similar considerations apply to other emergent concepts in continuum mechanics such as viscosity, elasticity, tensile strength, etc.
- Classical mechanics: The laws of classical mechanics can be said to emerge as a limiting case from the rules of quantum mechanics applied to large enough masses. This may be puzzling, because quantum mechanics is generally thought of as *more* complicated than classical mechanics.
- Statistical mechanics was initially derived using the concept of a large enough ensemble that fluctuations about the most

likely distribution can be all but ignored. However, small clusters do not exhibit sharp first order phase transitions such as melting, and at the boundary it is not possible to completely categorize the cluster as a liquid or solid, since these concepts are (without extra definitions) only applicable to macroscopic systems. Describing a system using statistical mechanics methods is much simpler than using a low-level atomistic approach.
- Weather
- Patterned ground: the distinct, and often symmetrical geometric shapes formed by ground material in periglacial regions.

Temperature is sometimes used as an example of an emergent macroscopic behaviour. In classical dynamics, a *snapshot* of the instantaneous momenta of a large number of particles at equilibrium is sufficient to find the average kinetic energy per degree of freedom which is proportional to the temperature. For a small number of particles the instantaneous momenta at a given time are not statistically sufficient to determine the temperature of the system. However, using the ergodic hypothesis, the temperature can still be obtained to arbitrary precision by further averaging the momenta over a long enough time.

Convection in a fluid or gas is another example of emergent macroscopic behaviour that makes sense only when considering differentials of temperature. Convection cells, particularly Bénard cells, are an example of a self-organizing system (more specifically, a dissipative system) whose structure is determined both by the constraints of the system and by random perturbations: the possible realizations of the shape and size of the cells depends on the temperature gradient as well as the nature of the fluid and shape of the container, but which configurations are actually realized is due to random perturbations (thus these systems exhibit a form of symmetry breaking).

In some theories of particle physics, even such basic structures as mass, space, and time are viewed as emergent phenomena, arising from more fundamental concepts such as the Higgs boson or strings. In some interpretations of quantum mechanics, the perception of a deterministic reality, in which all objects have a definite position, momentum, and so forth, is actually an emergent phenomenon, with the true state of matter being described instead by a wavefunction which need not have a single position or momentum. Most of the laws of physics themselves as we experience them today appear to have emerged during the course of time making emergence the most fundamental principle in the universe and raising the question of what might be the most fundamental law of physics from which all others emerged. Chemistry can in turn be viewed as an emergent property of the laws of physics. Biology (including biological evolution) can be viewed as an emergent property of the laws of chemistry. Finally, psychology could at least theoretically be understood as an emergent property of neurobiological laws.

Living, biological systems

Life is a major source of complexity, and evolution is the major principle or driving force behind life. In this view, evolution is the main reason for the growth of complexity in the natural world. If we speak of the emergence of complex living beings and life-forms, we refer therefore to processes of sudden changes in evolution.

Flocking is a well-known behaviour in many animal species from swarming locusts to fish and birds. Emergent structures are a common strategy found in many animal groups: colonies of ants, mounds built by termites, swarms of bees, shoals/schools of fish, flocks of birds, and herds/packs of mammals.

An example to consider in detail is an ant colony. The queen does not give direct orders and does not tell the ants what to do. Instead, each ant reacts to stimuli in the form of chemical scent from larvae, other ants, intruders, food and build up of waste, and leaves behind a chemical trail, which, in turn, provides a stimulus to other ants. Here each ant is an autonomous unit that reacts depending only on its local environment and the genetically encoded rules for its variety of ant. Despite the lack of centralized decision making, ant colonies exhibit complex behavior and have even been able to demonstrate the ability to solve geometric problems. For example, colonies routinely find the maximum distance from all colony entrances to dispose of dead bodies.

A broader example of emergent properties in biology is the combination of individual atoms to form molecules such as polypeptide chains, which in turn fold and refold to form proteins. These proteins, assuming their functional status from their spatial conformation, interact together to achieve higher biological functions and eventually create - organelles, cells, tissues, organs, organ systems, organisms. Cascade phenotype reactions, as detailed in Chaos theory, may arise from individual genes mutating respective positioning.[4] In turn, all the biological communities in the world form the biosphere, where its human participants form societies, and the complex interactions of meta-social systems such as the stock market.

Emergence in culture and engineering

Emergent processes or behaviours can be seen in many places, such as traffic patterns, cities, political systems of governance, cabal and market-dominant minority phenomena in politics and economics, organizational phenomena in computer simulations and cellular automata.

Economics

The stock market is an example of emergence on a grand scale. As a whole it precisely regulates the relative security prices of companies across the world, yet it has no leader; there is no one entity which controls the workings of the entire market. Agents, or investors, have knowledge of only a limited number of companies within their portfolio, and must follow the regulatory rules of the market and analyse the transactions individually or in large groupings. Trends and patterns emerge which are studied intensively by technical analysts.

World Wide Web & Internet

The World Wide Web (WWW) is a popular example of a decentralized system exhibiting emergent properties. There is no central organization rationing the number of links, yet the number of links pointing to each page follows a power law in which a few pages are linked to many times and most pages are seldom linked to. A related property of the network of links in the world wide web is that almost any pair of pages can be connected to each other through a relatively short chain of links. Although relatively well known now, this property was initially unexpected in an unregulated network. It is shared with many other types of networks called small-world networks.(Barabasi, Jeong, & Albert 1999, pp. 130-131)

Internet traffic also exhibits several emergent properties. The burstiness of Internet traffic has been well-noted as a fractal or self-similar distribution (Leland et. al. 1994, pp. 1-15). This self-similar traffic has been found to have a similar Hurst exponent of approximately 0.8 (fractal dimension 1.2) in measurements of various Internet links around the world regardless of user profiles or traffic types (web, email, P2P, etc.). In addition, due to the congestion control mechanism, TCP flows can become globally synchronized at bottlenecks simultaneously increasing and then decreasing throughput in coordination. Congestion, widely regarded as a nuisance, is an emergent property of the spreading of bottlenecks across a network in high traffic flows which can be considered as a phase transition (see review of related research in (Smith 2008, pp. 1-31)).

Architecture and cities

Emergent structures appear at many different levels of organization or as spontaneous order. Emergent self-organization appears frequently in cities where no planning or zoning entity predetermines the layout of the city. (Krugman 1996, pp. 9-29) The interdisciplinary study of emergent behaviors is not generally considered a homogeneous field, but divided across its application or problem domains.

Often architects and landscapers will not design all the pathways of a complex of buildings. Instead they will let usage patterns emerge and then place pavement where pathways have become worn in.

The on-course action and vehicle progression of the 2007 Urban Challenge could possibly be regarded as an example of cybernetic emergence. Patterns of road use, nondeterministic obstacle clearance times, etc. will work together to form a complex emergent pattern that can not be deterministically planned in advance.

Mathematics

A Möbius strip in mathematics demonstrates emergence

Although the above examples of emergence are often contentious, mathematics provides a rigorous basis for defining and demonstrating emergence. In Emergence is coupled to scope, not level, Alex Ryan shows that a Möbius strip has emergent properties (Ryan 2006). The Möbius strip is a one-sided, one-edged surface. Further, a Möbius strip can be constructed from a set of two-sided, three edged, triangular surfaces. Only the complete set of triangles is one-sided and one-edged: any subset does not share these properties. Therefore, the emergent property can be said to emerge precisely when the final piece of the Möbius strip is put in place. An emergent property is a spatially or temporally extended feature – it is coupled to a definite scope, and cannot be found in any component because the components are associated with a narrower scope.

Pithily, emergent properties are those that are global, topological properties of the whole.

Language

It has been argued that language, or at least language change, are emergence phenomena. While each speaker merely tries to reach his own communicative goals, he uses language in a particular way. If enough speakers behave in that way, language is changed (Keller 1994).

Fads and beliefs

An **emergent concept** (EC) is a slight variation on consensus reality that is accepted as plausible. The hallmarks of an emergent concept, as opposed to some categories of Internet memes/phenomena, urban myths, or the like, are that EC are increasingly accepted as truth or plausible, based upon other empirical or anecdotal evidence in the mind of the believer or society (in its subsets) as a whole.

Emergence in political philosophy

Economist and philosopher Friedrich Hayek wrote about emergence in the context of law, politics, and markets. His theories are most fully developed in Law, Legislation and Liberty, which sets out the difference between *cosmos* or "grown order" (that is, emergence), and *taxis* or "made order". Hayek dismisses philosophies that do not adequately recognize the emergent nature of society, and which describe it as the conscious creation of a rational agent (be it God, the Sovereign, or any kind of personified body politic, such as Hegel's state or Hobbes's leviathan). The most important social structures, including the laws ("nomos") governing the relations between individual persons, are emergent, according to Hayek. While the idea of laws and markets as emergent phenomena comes fairly naturally to an economist, and was indeed present in the works of early economists such as Bernard Mandeville, David Hume, and Adam Smith, Hayek traces the development of ideas based on spontaneous-order throughout the history of Western thought, occasionally going as far back as the presocratics. In this, he follows Karl Popper, who blamed the idea of the state as a made order on Plato in *The Open Society and its Enemies*.

Emergence in organisational theory

Emergence is referred to as the complex process whereby the right person or idea *emerges* exactly at the right moment. Just when a problem occurs or a necessity, the potential solutions also emerges.

See also

- Anthropic principle
- Causality
- Chaos theory
- Collective intelligence
- Collectivism
- Complex systems
- Conatus
- Connectionism
- Constructal theory
- Dynamical system
- Determinism
- Emergent algorithms
- Epiphenomenon
- Emergence Phenomenon
- Emergent gameplay
- Flocking (behaviour)
- Fractal
- Free will
- Generative sciences
- Holism
- Interaction
- Interconnectedness
- Mass action
- Neural networks
- Process Physics
- Reductionism
- Self-organization
- Society of Mind theory
- Spontaneous order
- Swarm intelligence
- Systems intelligence
- Systems thinking
- System of Systems
- Unintended consequence
- Market-dominant minority

Notes

1. ^ Aristotle, *Metaphysics*, Book H, 1045b:8-10
2. ^ "The chemical combination of two substances produces, as is well known, a third substance with properties different from those of either of the two substances separately, or of both of them taken together" (Mill 1843)
3. ^ Julian Huxley: "now and again there is a sudden rapid passage to a totally new and more comprehensive type of order or organization, with quite new emergent properties, and involving quite new methods of further evolution" (Huxley & Huxley 1947)
4. ^ Campbell, Neil A., and Jane B. Reece. Biology. 6th ed. San Francisco: Benjamin Cummings, 2002.

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External links

- *Emergence: Complexity and Organization*, quarterly journal, ISSN: 1521-3250.
- ISCE group: Institute for the Study of Coherence and Emergence.
- The Complexity Society: "The Application of Complexity Science to Human Affairs".
- Universal Automatism - Everything is Computation
- Exploring Emergence: An introduction to emergence using CA and Conway's Game of Life from the MIT Media Lab
- Emergence of property rights: a game theory model
- An interview with Stephen Johnson
- Stanford Encyclopedia of Philosophy entry on Emergent Properties
- Emergence Versus Self-Organisation: Different Concepts but Promising When Combined: paper on the difference between emergence and self-organization.
- Emergent Economics: discussion of emergent vs. natural phenomena and emergent vs. deterministic phenomena; as well as language and markets as examples of emergent phenomena.
- Emergent Systems Working Group: Center for Science in Society, Bryn Mawr College
- Jean-Louis Dessalles: present texts concerning emergence
- Complexity Virtual Laboratory (VLAB) Demonstrations of emergence in various complex systems

Specialized wikis

- DCS-Wiki
- NECSI Wiki
- Shalizi's Notebooks

Robotics

- "Designing Emergent behaviours: From Local Interactions to Collective Intelligence", Maja J. Mataric, *From Animals to Animats 2*; Meyer, J-A., etal (eds)
- "Towards a Theory of Emergent Functionality", Luc Steels, *From Animals to Animats 1*, Meyer, J-A. & Wilson, S. (eds)

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