Emergence in inert matter: A message to life and social sciences

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Abstract: The concept of emerging behavior is central to complexity studies in biology, psychology, sociology, politics, economics and organization management. Many, if not most, approaches are based on the belief that emergence be something limited to living organisms and social super-organisms. However, while easier to encounter in systems of that sort, emergence belongs in the physical world as well. We contend that without such consciousness, anti-reductionism collapses to a banal vitalistic view where the laws of biology do not complement, but surpass and often contradict the laws of physics. The very fact, instead, that emerging behavior is a physical feature allows for a radical critique of reductionism, showing that at each geometrical level of Nature (quark, neutron, nucleus, atom, molecule, virus, cell, etc.) new sets of laws may appear that, while compatible with the lower-level ones, introduce new knowledge.

1. Introduction

Insect colonies, flights of birds, human aggregates, cyclones and financial markets are all examples of situations where systems sometimes behave in a way that cannot be explained on the sole grounds of the laws governing their constituent components. For example, non-deterministic behavior may emerge from groups of elements each obeying deterministic laws [1][2], or a collective behavior may emerge that is far richer than that of any individual [3][4][5].

This has long been a subject of speculation in biology, psychology, sociology, politics, economics, organization science and other disciplines. In these domains it is common to refer to emergence as either an exclusive property of living organisms or a form of “intelligent” self-organizazion.

For example (the italics are ours): «The science of complexity studies how single elements, such as a species or a stock, *spontaneously* organize into complicated structures like ecosystems and economies; stars become galaxies, and snowflakes avalanches almost as if these systems were obeying a *hidden yearning* for order» [6]. Or again: «Emergence is what happens when an interconnected system of relatively simple elements *self-organizes* to form more *intelligent*, more adaptive higher-level behavior. [...] Systems that at first glance seem vastly different –ant colonies, human brains, cities, immune systems– all turn out to follow the rules of emergence».[7] For Stuart Kauffman [8], self-organization («order for free») can be used to explain the transition from inert matter to living cells, and this view is supported by earlier biological studies [9].

We do not discuss, much less argue against, the view of emerging behavior as part of the paradigm for life or its explanation thereof.

We simply observe that such approach diminishes the depth of anti-reductionism and encourages an unnecessary separation between physical and life sciences, which should rather be seen in a continuum of increasing complexity.

2. Hints from physics

Since almost half-a-century physicists have shown that emergence can be observed at work in collections of subatomic particles.

We owe the first such proof to Philip W. Anderson, who published it in a paper in the early Seventies [10]: just like a bunch of sports fans or a flock of birds sometimes do things which are not explained by individual attitudes, equally so electrons in a superconductor, when observed not one by one but rather as sets, may exhibit behaviors that are unpredictable by using the physical laws that govern the motion of the electron.

It is therefore necessary to find the laws for the aggregates, the systems, as opposed to just the "elementary" ones. (As Anderson himself clarified many times, emergent complex phenomena are not violations of the microscopic laws: they simply «do not appear as logically consequent» on them [11]).

That finding closed the door to reductionist dreams, i.e. the hope to find out everything about Nature by merely discovering the fundamental laws of physics.

This, however, was never communicated effectively outside the physical community, despite Anderson gaining a Nobel Price in 1977 for related works. Because of the grandiose scale, the cost and the mediatic impact of projects such as linear super-accelerators or spacecraft-mounted probes and telescopes, the news that usually make it out of the world of physics are those concerning the two extreme fields of elementary particles and astrophysics. News from other sub-domains of physical research rarely make it to life scientists or social scientists.

The *mesoscale* is the geometrical level of matter where neither *age* is much relevant (as it is for galaxies) or it is useful to regard structures as groups of elementary particles (like in an atom), because these are far too many and statistical means or higher-level laws become necessary. This sub-domain of physics has always been a hotbed for powerful applications, such as X-rays or transistors or lasers, but it was never regarded as a source of better explanations of Nature like it happened with subatomic physics or astrophysics.

It is therefore not surprising that the consciousness of emergence as a physical phenomenon has not made it yet to the mainstream of complex studies outside of physics.

3. Linearity and predictability

In physics, emergence is the result of interactions between the components of a system: it is these interactions that render the essential non-linearity of all systems apparent.

For centuries, scientists have been using the linearity approximation in order to manage particularly hard problems. A problem is linear if it can be broken into a sum of mutually independent sub-problems. When, on the contrary, the various components/aspects of a problem interact with each other so as to render impossible their separation for solving the problem step by step or in blocks, then the situation is non-linear. Another way to express the same concept is to use the (equivalent) systems theory definition: a system is linear if it responds with direct proportionality to inputs. This is a system that obeys the superposition principle: the response at a given place and time caused by two or more stimuli is the sum of the responses which would have been caused by each stimulus individually [12].

Linear models are useful because subject to the hypothesis of linearity many natural systems resemble one another: their behavior can be described with mathematical equations and the equations look the same even if the contexts are very different, such as mechanics, electronics, chemistry, biology, economics, and so on. E.g., a linear oscillator is a model described by the same mathematical equation, whether it be a metal spring, an electric circuit or a standalone El Niño.

Enormous scientific and technological advances have been made using simplifying linearity assumptions, and it was not until computers allowed to venture into non-linear territory that “complexity science” was really born.

3.1 Enter computers

There had been, in fact, several explorations of non-linearity since the late 19th century, by, among others, Poincaré, Lyapunov, Bogdanov, Volterra, Wiener and Weaver [13]. However, the field remained little more than a curiosity until the advent of electronic computers, as they make it possible to simulate whenever mathematics does not do the job due to unknown or unsolvable equations.

Fundamental, in this respect, was the work of mathematician and climatologist Edward Lorenz [14], who provided experimental dignity to the problem that Henri Poincaré had touched upon in the three-body system: When observing the trajectory in state-space of a system over time, *finite* variations may originate from *infinitesimal* variations in the initial conditions. In other words, even two infinitely similar beginnings will look different in the future, because the evolution of the system will differ substantially in the two cases, with a divergence ever-larger in time.

Making predictions about the future state of a system is therefore impossible, at least in principle. Only linear systems are predictable in both practice and theory.

A system is not linear, or non-linear, if it does not satisfy the superposition principle: its response at a given place and time caused by two or more stimuli is not necessarily the sum of the responses which would have been caused by each stimulus individually.

This is what all "systems" and "problems" we encounter in Nature really are: they only become linear when we want them to be so for application purposes, within specified performance or time limits. Linearity is not a feature distinguishing "easy" systems from more difficult ones: it is a conceptual artefact, a simplified model. All systems are non-linear and perhaps the best definition of the word "system" is that of *a set of parts that, when acting as a whole, produces effects that the individual parts cannot* [15].

3.2 Some effects of non-linearity

The properties of a linear system are additive: the effect of a collection of elements is the sum of the effects when they are considered separately, and overall there appear no new properties that are not already present in the individual elements. But if there are elements/parts that are combined, depending on one another, then the complex is different (not necessarily "greater", as is commonly believed) from the sum of the parts and new effects start to appear [16]. For example, stimulus S at time t_2 may provoke a system response $R(t_2)$ different from $R(t_1)$ to the same stimulus: non-determinism.

Furthermore, in its most general definition, the superposition principle subsumes *homogeneity*, meaning that if the input is multiplied (divided) by some quantity the output will increase (decrease) by the same measure. Qualitatively, we could say that in a homogeneous system a modification to the components is proportionally reflected in a modification of the whole.

Non-linear systems are non-homogeneous: a modification of the components is not necessarily proportional to a modification of the whole or, which is the same, a modification of the input signal does not necessarily modify the output proportionally.

As an example, the oscillations of an electric circuit remain predictable only within a range of the input currents where its characteristic properties are approximately homogeneous. Outside that range, it can no longer be assumed that resistance, capacity and inductance are exclusively concentrated on resistors, capacitors and inductors: in reality, these characteristics are distributed along the entire circuit, and outside a limited frequency range these non-linear effects can manifest themselves impetuously and chaotically. The same can be said of mechanical oscillators and all oscillating phenomena in general (such as, e.g., cyclones).

Not only do all these features make the behavior of a non-linear system unpredictable: but since the behavior of the a whole does not necessarily reflect that of the composing elements, a "systemic behavior" emerges which even a perfect knowledge of the components cannot account for. To understand the system, we need to know both about the components (analysis) and about the whole (holism).

4. Emergence

Emerging behavior is easier to encounter in systems made of living organisms or in economic and social systems, because, unlike electrons in superconducting material, these are the things that we experience every day and because they often are more complicated (i.e. with many parts and subparts, often hidden) than physical systems.

But it is essential to realize that emergence belongs in the physical world as well. Without such consciousness, the anti-reductionistic approach would be diminished: it would collapse to a banal vitalistic [17] view of the world where the laws of biology do not complement, but surpass and often contradict the laws of physics.

The very fact, instead, that emerging behavior is a physical feature attests its importance at the epistemological level: on its grounds, a radical critique of reductionism can be developed, showing that the laws of particle physics are insufficient to explain the behavior of aggregates of electrons or atoms, as much as those of chemistry are not enough to explain the behavior of molecule aggregates, and that at each geometrical level of Nature (quark, neutron, nucleus, atom, molecule, virus, life cell, etc.) new sets of laws may appear that, while compatible with the lower-level ones, introduce new knowledge.

4.1 Other examples

Other physical situations that can be ascribed to emergence, or at least can offer an intuitive grasp of the role of emergence outside of living and social systems, include the following:

- The particles that make up atoms do not have a color. Protons or electrons are not green or yellow or red, because they do not absorb or emit visible light. Groups of atoms though, i.e. aggregates of those particles, do have colors;
- Many properties of condensed matter (ordinary matter), such as viscosity, friction or elasticity, are extraneous to the composing atoms and molecules. They emerge as properties of large aggregates of molecules;
- Aggregates of atoms, like the ordinary matter that we experience every day, do not seem to obey the laws of quantum mechanics. *Quantum decoherence*, that is the offsetting of phase angles among elementary particles in a system, is the phenomenon that causes this, making classical physics emerge out of an underlying quantistic world;
- The laws of elementary particles are indifferent to the direction of time. If one changes from positive to negative the sign of variable t in Schroedinger's equation, nothing changes in the results. That is to say, at the microscopic level Nature looks the same whether we go forward or backward in time. This is not what we observe at the mesoscale: “an omelette never returned to being an egg”. The variable we call time can be defined as an effect, not a cause, of increasing entropy: the *arrow of time* is an emerging property of statistical mechanics.

5. Conclusions

The observation and study of emerging phenomena can get extraordinarily complex, especially when living organisms and human populations are concerned. However, awareness of the elementary foundations of emergence is needed if one is to analyze such phenomena of extreme complexity.

It is not difficult to find complexity in a child's behavior or in that of the global financial system: indeed, in those cases, the qualification as “complex system” can be so trivial as to lose all useful meaning. But complexity is more telling when it is found in basic physical systems, because this is an area that we understand better than that of living or social systems, which are less amenable to mathematical modeling and organized experimentation.

To truly master phenomena, we must understand their essence. So, if we can recognize “complex adaptive” behavior in the physical, inanimate and inorganic world, perhaps we will know something better. This, on the other hand, is not to deny the existence of complex phenomena that have no “fundamental” physical explanation: such a denial would be reductionism, because it would amount to saying that every phenomenon can be explained by the laws of elementary particles.

References

[1] Poincaré, H., "Sur le problème des trois corps et les équations de la dynamique", Acta Mathematica, Vol. 13, 1890, pp. 1–270

[2] May, R. M., "Simple mathematical models with very complicated dynamics", Nature, Vol. 261, 1976, p. 459

[3] Gardner, M., “The fantastic combinations of John Conway's new solitaire game «life»”, *Scientific American*, N.223, 1970, p.120

[4] John Holland, *Adaptation in Natural and Artificial Systems*, University of Michigan Press 1975

[5] S. Kauffman, *The Origins of Order: Self-Organization and Selection in Evolution*, Oxford University Press, 1993

[6] M. Waldrop, *Complexity: the emerging science at the edge of order and chaos*, Simon & Schuster, 1992, p. 380

[7] S. Johnson, *Emergence: The Connected Lives of Ants, Brains, Cities, and Software,* Scribner 2011,

and <https://wiki.umn.edu/pub/DHA5399/Clas13A/DHA5399_Emergencetalk.pdf> accessed 03 February 2012

[8] Kauffman, S., *At home in the universe: the search for laws of self-organization and complexity*, Oxford University Press, 1995, p. 281

[9] Eigen, M., P. Schuster, *The Hypercycle: A Principle of Natural Self-Organization*, Springer-Verlag, 1979

[10] Anderson, P. W., “More Is Different”, *Science*, New Series, Vol. 177, No. 4047, 1972, pp. 393-396

[11] Anderson, P. W., “Physics: The opening to complexity”, Colloquium Paper, *Proc. Natl. Acad. Sci.*, USA, vol. 92, July 1995, p. 6653

[12] R.P. Feynman, R. Leighton, M. Sands, *The Feynman Lectures on Physics*, Addison-Wesley, Vol. 1, 1964, p. 25-3.

[13] P. Magrassi, *Difendersi dalla complessità*, Franco Angeli 2009, pp. 23-33

[14] Lorenz, E., "Deterministic Nonperiodic Flow", *Journal of the Atmospheric Sciences*, Vol. 20, 1963, pp. 130-141

[15] Minati, G. and Pessa, E. (2006) *Collective Beings*, Springer, p. 23

[16] P. Bridgman, *The Logic of Modern Physics*, The Mac-Millan Company, New York 1927, pag. 42

[17] F. T. Arecchi, *Caos e complessità nel vivente*, Multimedia Cardano 2004, pag. 67