Fifty years of "More is different"

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ABSTRACT

August 1972 saw the publication of Philip Anderson's essay "More is different". In it, he crystallized the idea of emergence, arguing that "at each level of complexity entirely new properties appear" — that is, although, for example, chemistry is subject to the laws of physics, we cannot infer the field of chemistry from our knowledge of physics. Fifty years on from this landmark publication, eight scientists describe the most interesting phenomena that emerge in their fields.

Steven Strogatz: More than the sum

In 1665, while confined to his room with "a slight indisposition", Christiaan Huygens noticed that two pendulum clocks he had recently built were keeping perfect time together. When one clock's pendulum swung to the right, the other's swung to the left, exactly 180 degrees out of phase. When Huygens tried disturbing their oscillations, he found to his astonishment that the board from which both clocks were suspended began to jiggle. That jiggling gradually nudged the pendulums back into antiphase synchrony. In letters to his correspondents, he described this "odd sympathy" of clocks as "marvelous".

Huygens's work launched the study of synchronization, a phenomenon that pervades the natural and technological world, from congregations of fireflies that flash in unison to arrays of superconducting Josephson junctions. Yet although more than 350 years have passed since Huygens's observations, we still don't fully understand the sympathy of pendulum clocks mathematically.

The main obstacle is that synchronization is a nonlinear phenomenon, which makes the governing equations impossible to solve explicitly. On top of that, the equations include non-smooth, impulsive effects, stemming from the sudden jolts imparted by the clocks' escapement mechanisms.

In this way, the sympathy of clocks exemplifies what Philip Anderson discussed in "More is different"[1]. Even though we know the laws for individual pendulum clocks, that isn't enough to tell us how two or more of them will behave together.

Sara Walker: Broken symmetry

In the study of life's origin, one cannot avoid emergence. Life itself is an emergent property: a cell is alive, but its parts are not. To adopt Anderson's words, the ability to reduce life to simple fundamental parts does not imply the ability to start from those parts and reconstruct life. Indeed, attempts to solve the origin of life have not yet succeeded, even though we have detailed knowledge of molecular biology.

What are we missing? The answer is ordering in time – life is historically contingent. Darwin spoke of "endless forms most beautiful" in contradistinction to Newton's fixed law of gravity[2] for good reason: only in living things do we see path-dependence and mixing of histories to generate new forms; each evolutionary innovation builds on those that came before, and often these innovations interact across time, with more ancient forms interacting with more modern ones.

Anderson argued that broken symmetries underlie emergence. The broken symmetry of time is most obvious in looking at life's parts. Even macromolecules like proteins, DNA and RNA are still part of 'life' if not alive: they do not emerge in the Universe without an evolutionary process selecting machinery to assemble them[3]. This ordering in time is driven by life's "information-bearing crystallinity", as Anderson put it. Each innovation, whether a mutation in a genome or in human language, yields affordances for future events in a manner different from the directionality in time illuminated in the second law of thermodynamics. If we are to explain the emergence of life, we need to understand how information breaks symmetry in time.

Julia Yeomans: Self-assembly and control mechanisms

Living systems are highly complex machines: cells need to assemble molecular structures that can use chemical energy to perform the complex tasks needed for life processes. The challenges of creating artificial cells underline the intricacy of the emergent self-assembly and control mechanisms that enable life to function.

For example, cells need a way to internally transport cargo. They achieve this using a continually evolving network of tracks consisting of polymeric filaments that grow and disassemble, on which motor proteins carry their loads. In another example, bacteria swim using a rotary motor to turn their flagella at speeds of about 500 revolutions per minute. The motor is an organized array of specialized proteins, about 45 nm in diameter. These form a rotor, driven by a proton flux, which spins relative to the cell within a stator which is anchored to the cell wall. And an embryo is transformed from a small ball of cells to a grown animal by a sequence of steps that involve movements and division of localized groups of cells. Each step must be programmed to occur at specific places and times.

How are these examples of self-assembly and morphogenesis mediated? Living systems operate out of thermodynamic equilibrium. Hence they are increasingly being described using the ideas of active matter physics, which treats materials where each particle continually uses energy to move. Studies of self-assembly in active systems may give insight into the extent to which there are underlying, generic principles at work in biological design, which can then be used to help fabricate efficient microscopic machines.

Corina Tarnita: Emerging patterns

Unparalleled architectural feats, division of labour, agriculture and animal husbandry — although these might sound like uniquely human achievements, I am actually referring to insect societies, such as those of ants and termites, whose internal organization abounds with emergent phenomena: no individual properties of the minute insects could foreshadow the mind-boggling complexity that millions together can achieve.

I spent years marvelling at colony organization, but the greatest surprise came when I looked outside any one colony. Social insects' capacity for self-organization extends to landscape scales and is accompanied by emergent properties that impact ecosystems[4,5]. As fiercely competitive with their neighbouring colonies as they are cooperative with their colony-mates, termites carve out the landscape into a hexagonal pattern of defended territories surrounding each colony. Smaller colonies are obliterated in wars of attrition, leaving a kilometres-scale polka-dot spattering of equal-sized and equidistant giants.

Such colonies can live for decades but can create centuries-long legacies when their painstakingly built mounds get recolonized after the founders' deaths[6]. Owing to termites' soil engineering and nutrient cycling, each mound has properties that differ from those of the between-mound matrix, such as different and more diverse microbial communities[7], different and more productive plant communities[7], higher abundance of insects and arthropods, or more frequent use by herbivores. But the emergent spatial patterning of the mounds has ecosystem-wide consequences that could not be predicted from the properties of individual mounds, much less from those of individual termites. The thousands of hexagonally distributed mounds altogether boost microbial diversity and ecosystem productivity more than if the same mounds had been randomly scattered[7,8], and they are predicted to substantially enhance ecosystem robustness to climatic perturbations.

Elsa Arcaute: Flows of innovation

Cities present many of the emergent behaviours characterizing eusocial animals such as division of labour and specialization. These result from exchanges of information at the local level, modulated through different mechanisms and constraints. In the case of human societies, our interactions are constantly regulated by path dependencies, and fine-tuned through mixing and memory, leading to mechanisms that go beyond our basic needs for survival. This is the case of any process related to learning, where the status quo of our collective knowledge is progressively updated, generating unforeseen innovations, creating new communities and activities that transcend physical, cultural and political boundaries, impacting the whole planet and beyond.

For example, the late 1960s and early 1970s experienced an information field — in the mathematical sense — permeating the different academic communities, leading to the general ideas behind complexity science to emerge in many different disciplines around the same time. Such a field corresponds to the flow of information through direct or indirect interactions. In the past, the information flow was strongly modulated by the speed of transportation, which also constrained urban development. Our street networks, for example, are fractal structures that have been collectively generated as the result of reinforcing interactions between places that were important through time.

We have now been able to develop means of communicating large amounts of information quasi-instantly across any distance within the planet. Nevertheless, as recently seen, face-to-face interactions remain pivotal for innovation, and cities are at the heart of enabling these through the mixing of ideas.

Manlio De Domenico and Oriol Artime: Systems of systems

Many emergent phenomena are sustained through networks of interactions. Focusing, for instance, on biophysical phenomena, we have biomolecular interactions emerging from the human interactome, or electrochemical neural connectivity patterns emerging from the human connectome. In general, though, these networks do not operate in isolation: they are coupled to each other by means of structural or functional interdependencies, and they are organized in multiple contexts of interactions, also known as layers. These layers may include links that are spatial, temporal, informational or combinations thereof.

Switching perspective from single- network to multilayer analysis allowed for the discovery of a plethora of emerging physical phenomena not observed in non-interacting systems, indissolubly related with Anderson's more-is-different paradigm. An emblematic example is related to the robustness properties of multilayer networks: the failure of a single node can trigger cascade failures that propagate via interdependencies across the multilayer system, leading to abrupt and system-wide collapses that are extremely difficult to anticipate. Another example concerns intertwined spreading processes and the emergence of a metacritical point, separating the regime in which the critical properties of one process do not depend on those of the other processes, and the regime in which those properties are interdependent[9].

The multilayer nature of biophysical systems pushes our understanding of biological functions well beyond the traditional reductionist hypotheses, and our knowledge of pathogenesis well beyond simple single-gene mutations leading to Mendelian disorders: at the molecular level, life and disease are emergent phenomena depending on highly interconnected, multilayer and multiscale interactions whose study, culminating in the fields of network medicine, systems biology and systems medicine, provides exciting research directions for the next years.

Kwang-Il Goh: New singularities

I was fortunate enough to begin my career in statistical physics when the modern theory of complex networks was beginning to germinate. From early days, I have often been asked the question, "Why care about networks as physicists?" I could best answer it by following lessons from such giants as Phil Anderson, whose 1972 essay we are celebrating here. In the parlance of Anderson, a key dictum of complex network theory is that when a large number of degrees of freedom interact through non-trivial but organized networks, new and unforeseen collective phenomena can emerge.

The network pattern presents an additional facet of complexity, on top of which many-body physics can further take place. Many-body physics on networks can often be solved using a mean-field approach, offering rare examples in physics in which mean-field solutions can be compared with reality. Moreover, in the most engaging cases, the resulting mean-field theories come with singularities not seen in other systems. Phenomena such as the null epidemic threshold on scale-free networks — the fact that epidemics can spread on scale-free networks even in the limit that the infection rate goes to zero — find their theoretical origin in such new singularities that non-trivial network patterns entail. Developments including multiplex networks and, more recently, higher-order networks follow this tradition of sorting out what new emergent singularities there are. I wonder if Anderson foresaw all this when he mentioned "...still fascinating questions of principles about glasses and other amorphous phases, which may reveal even more complex types of behaviour", but in regard to network science I have always felt, and will continue to feel, that I am following in the footsteps of Anderson.

References

1. Anderson, P. W. More is different: broken symmetry and the nature of the hierarchical structure of science. *Science* **177**, 393–396 (1972).

2. Darwin, C. *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life* (John Murray, 1859).

3. Marshall, S. M. *et al.* Identifying molecules as biosignatures with assembly theory and mass spectrometry. *Nat. Commun.* **12**, 1–9 (2021).

4. Pringle, R. M. & Tarnita, C. E. Spatial self-organization of ecosystems: integrating multiple mechanisms of regular-pattern formation. *Annu. review Entomol.* **62**, 359–377 (2017).

5. Sundaram, M., Steiner, E. & Gordon, D. M. Rainfall, neighbors, and foraging: The dynamics of a population of red harvester ant colonies 1988–2019. *Ecol. Monogr.* **92**, e1503 (2022).

6. Watson, J. A termite mound in an iron age burial ground in rhodesia. *The J. Ecol.* 663–669 (1967).

7. Baker, C. C. *et al.* Spatial patterning of soil microbial communities created by fungus-farming termites. *Mol. Ecol.* **29**, 4487–4501 (2020).

8. Pringle, R. M., Doak, D. F., Brody, A. K., Jocqué, R. & Palmer, T. M. Spatial pattern enhances ecosystem functioning in an african savanna. *PLoS biology* **8**, e1000377 (2010).

9. De Domenico, M., Granell, C., Porter, M. A. & Arenas, A. The physics of spreading processes in multilayer networks. *Nat. Phys.* **12**, 901–906 (2016).