The impact of the paradigm of complexity on the foundational frameworks of biology and cognitive science

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1. INTRODUCTION: TWO TRADITIONAL WAYS OF DOING SCIENCE

- For most people, scientific activity consists in discovering general principles capable to express large regularities of the world (“natural laws”) and formulate them in mathematical terms.
- These mathematically expressed laws will allow, starting from a set of observables, predict the future state of any natural system.

> predictability through mathematical models

1. INTRODUCTION: TWO TRADITIONAL WAYS OF DOING SCIENCE

This is the so-called “nomological-deductive” model. It is a way of doing science based in the discovery of laws: explaining a phenomenon means subsuming it under a law

And scientific progress is seen as the discovery of new, increasingly encompassing laws

This model of doing science has been very successful since XVIIth Century, specially in Physics and Chemistry.

1. INTRODUCTION: TWO TRADITIONAL WAYS OF DOING SCIENCE

However, this model has been unsuccessful when dealing with biological and cognitive systems, because of

* the huge quantity of interacting elements

* the non-linearity of the interactions

In addition, the interacting elements are hierarchically organized, and follow selective "rules"

1. INTRODUCTION: TWO TRADITIONAL WAYS OF DOING SCIENCE

This is why scientific progress in the study of biological and cognitive systems has mainly consisted in the discovery of explanatory mechanisms of how they work, rather than in the search of predictive laws

This is the so-called "mechanistic" model, which goes back to Descartes

1. INTRODUCTION: TWO TRADITIONAL WAYS OF DOING SCIENCE

Instead of looking for universally applicable laws or predictive models, biologists and cognitive scientists have searched to understand the behavior of living or cognitive systems by decomposing them into various parts, analyzing them separately, and investigating how these interrelate and affect one another within the whole system.

Since Descartes, the workings of life and mind (except human conscious mind) have been likened to the working of machines and physiology has been seeking to interpret the organism as a complicated set of mechanisms

1. INTRODUCTION: TWO TRADITIONAL WAYS OF DOING SCIENCE

- In the mechanistic tradition:
- • an explanation is viewed as the description of mappings between relevant functional operations and distinguishable structural components
- • an explanation consists in the decomposition of what is complex into simple processes and parts; and a re-composition of the complex phenomenon from the organization of these simpler processes/parts

1. INTRODUCTION: TWO TRADITIONAL WAYS OF DOING SCIENCE

- However, as our knowledge has been developed and fine-grained information becomes available, we are increasingly aware of new facts:
  - Recurrent, network-like interactions
  - Highly distributed and systemic organization
- • **In consequence, the atomistic-reductionist research program of the traditional mechanicism seems challenged**.

1. INTRODUCTION: TWO TRADITIONAL WAYS OF DOING SCIENCE

- For example
- at the end of the last century the reductionist program based on molecular biology that was centered in the discovery of the structure of the genome faced a dead end,
- since the more details were known, the more evidence was accumulated that genetic components acted in a complex web of interactions
- Thus, researchers started to look for the structure of regulatory networks at different levels (genomics, proteomics. . . .)

2. The Challenge of Complexity: understanding holistic systems

- We are discovering what has been called “emergent” or “self-organizing” phenomena [Yates, 1987]
  - This type of non-linear, collective phenomenon, which was found to occur in a large variety of domains (physics, chemistry, biology, ecology, neuroscience, society, . . .) shows the property that when a certain threshold in the number (and/or type) of interactions is reached, an emergent global pattern appears

2. The Challenge of Complexity: understanding holistic systems

Therefore, the global properties of these systems cannot be determined or explained by its component parts alone. Instead, the system as a whole determines in an important way how the parts behave (HOLISM)

In these systems analytical decomposition is not possible because their global emergent properties cannot be attributed to specific or well-distinguishable parts

2. The Challenge of Complexity: understanding holistic systems

- Until recent times, these systems challenged scientific understanding
  - because their behavior could not be easily predicted, and the specific forms of those patterns were never fully explained through available mathematical models
- However, the advent of the sciences of complexity has provided new tools and modeling techniques to really tackle scientifically some of those problematic phenomena
  - i.e., cellular automata, genetic algorithms, Boolean networks, chaos and dynamical systems theory…

2. The Challenge of Complexity: understanding holistic systems

- The study of the emergent behavior of holistic systems has been made possible thanks to the development of powerful computing models and machines
  - Although the dynamic processes leading to emergent behaviors are not analytically tractable, numerical methods, consisting in a fine-grained step-by-step update and recording of the state of all the interrelated variables of the system, allows the drawing of the state space of these systems
  - In this way, the evolution of the system is “synthetically” reproduced in the course of the simulation, rather than deduced for a given time value

2. The Challenge of Complexity: understanding holistic systems

→ Under these conditions, the prediction of the global property requires an enormous amount of parallel computation, where the complexity of the computational simulation is almost equivalent to that of the simulated system

2. The Challenge of Complexity: understanding holistic systems

- Following this methodology, different tools and models have been developed to discover generic properties of complex systems, often without a specific target system to fit and correspond with
- These models and tools are typically used to illustrate emergent properties, to discover universal patterns of connectivity in networks and their properties

2. The Challenge of Complexity: understanding holistic systems

- It is the concept of network and its mathematical and computational expressions that have provided the most fruitful metaphor and model for non-decomposable complex systems.
- The study of networks with strongly and recurrently interacting components has allowed scientists to deal with holistic systems, showing that, despite their variety, they share certain generic properties.

2. The Challenge of Complexity: understanding holistic systems

- Thus, by the end of the century a whole new scientific research program was initiated and seemed to be capable of grasping, with tools based on the increasing power of computers, (at least certain types of) prototypic holistic systems
- So, the blossoming of the sciences of complexity has induced a profound change in biology and cognitive sciences toward less analytic and more synthetic-holistic views

3. The specificity of the complexity of biological and cognitive systems

- However, the current view on Complex Systems does not capture the very essence of the complexity of biological and cognitive systems
- These systems are certainly made of a large number of parts or elements acting in non-linear ways, but they also show other features that are absent in non-living complex systems:
  - hierarchical organization
  - long-term sustainability
  - historicity
  - functional diversity
  - adaptivity and agency

3. The specificity of the complexity of biological and cognitive systems

→ Everywhere in biology and in cognitive science we deal with systems made of parts or elements with:

- different functionalities acting in a selective way
- coordinating themselves at different time scales
- interacting hierarchically in local networks, which
- form, in turn, global networks and, then, meta-networks. . .

3. The specificity of the complexity of biological and cognitive systems

- It is a type of complexity that goes beyond a mere increase in the “complicatedness” (i.e., an increase in the number and variety of components) of self-organizing systems:
- It involves qualitative changes in the form of organization of the system, by means of creating functionally differentiated structures and levels within it

3. The specificity of the complexity of biological and cognitive systems

- So here we are dealing not with mere complexity but with organized complexity as Weaver [1948] called it
- As J. Mattick (2004) has recently pointed out, what really matters in biological evolution is not so much the generation of complexity, but its functional and selective control

4. The organization of biological and cognitive systems: DD

- What does it consist of this organization, capable to functionally manage such huge complexity?
- Actually, what distinguishes biological and cognitive organizations lies in the role played by mechanisms of regulatory control in the functioning of these systems
- This means that biological and cognitive systems are internally organized in dynamically decoupled subsystems:
  - Since these subsystems work at different rates and with different operational rules, the system has an increased potential to explore new or alternative forms of global self-maintenance (that are not accessible to ‘flat’ systems without any hierarchy or modularity in their organization)

4. The organization of biological and cognitive systems: DD

- At the same time, the controlled level plays a fundamental role in the constitution and maintenance of the controller level (and therefore, of the whole system).
  - For example, the nervous system controls metabolic processes (circulation, digestion, breathing, etc.) on the one hand but, on the other hand, is fabricated and maintained by the latter

In other words, the organization is dynamically decoupled but functionally integrated

4. The organization of biological and cognitive systems: DD

- When the variations at the upper level find some pattern that contributes to the SM of the global organization, they are retained and become functional-regulatory constraints on the lower levels
- This way, DD allows a selective choice among a large amount of not-yet functional dynamical states (of the constitutive lower sub-system)
  - So that these selected states will contribute to the creation of new, more encompassing, processes of Self-Maintenance, thus becoming functional

4. The organization of biological and cognitive systems: DD

- For example, during evolution, living systems explore a large domain of genetic patterns, which hardly could be achieved at the ontogenetic level. This is possible because
- changes in the genetic domain are decoupled from the metabolic dynamics, this allows living systems to develop free compositionality and explore indefinitely a huge space of possibilities, finding through a selective process of retention (which takes place over whole populations and large space-temporal scales) new functional patterns of organization

5. A second-order form of holism

- Therefore, biological and cognitive systems convey specific forms of complexity that, through holistic-emergent processes (which are continuously taking place),
  - produce both dissipative patterns and
  - new, more complex structures which, in turn, are bound to become selective functional constraints acting on the dynamic processes that underlie those holistic processes.
- Those functional constraints can be described as **mechanisms** because they act as distinguishable parts (or collections of parts) related to particular tasks (e.g., catalytic regulation) performed in the system

5. A second-order form of holism

- So both aspects are, thus, complementary: the holism of the global network of processes and the local control devices/actions that are required for the system to increase in complexity
- Moreover, the newly created and functionally diverse constraints may give rise (once a certain degree of variety is reached) to new self-organizing holistic processes, which, in turn, may be functionally reorganized

5. A second-order form of holism

- In this way, an increase in organizational complexity can take the paradoxical form of an apparent "simplification" of the underlying complicatedness, giving rise to levels of organization in which a mechanistic de-compositional strategy might be locally applicable
- New hierarchical levels are created through a functional loss of details of the previous ones (Pattee, 1973)

6. The causal circularity

- The key point here is that this complementarity between functional mechanisms and holism, is due to their causal circularity.
- Since a mechanism is an explanation of the functioning of a system in terms of a specific arrangement of parts, it always sends one back to another mechanism to explain that arrangement of parts, and so on indefinitely.
- Thus, causal circularity is the only possible solution to the infinite regress posed by mechanistic explanations

6. The causal circularity

- And here is where the main difference between what we mean by a mechanistic explanation in a man-made system and in a natural one lies
- Actually, the organism-machine analogy brings biological and cognitive sciences closer to engineering than to physics or chemistry, as Polanyi [1968] sharply highlighted, arguing that both (organisms and machines) operate according to local rules (or 'boundary conditions') irreducible to general physico-chemical laws/principles

6. The causal circularity

- Whereas in man-made organizations structure and function are causally asymmetric (a given structure generates a given function, though not conversely)
- in biological and cognitive systems both structure and functions are engaged in a circular causal relation.
- Since what artificial machines do (i.e., their function) does not feed back to their own structure, machines must be externally designed and repaired

6. The causal circularity

- In contrast to artificial machines, in biological and cognitive systems the organization is internally generated, so the structure is itself the cause and the result of their functions.
  - If we compare a living cell with a computer, we can see that, although in both cases there is a highly complex internal structure, the computer functioning does not contribute to the maintenance of its own structure, whereas the cellular functioning is the cause of its structure

6. The causal circularity

- As a consequence, the structure and stability of living systems are not independent of their functions but, on the contrary, the functional level feeds-back to the structural one.
  - Parts do not do useful operations by external design; they do what they do because otherwise the system would disintegrate and they would cease to exist.
- There is, thus, a circular co-dependence between the stability or self-maintenance of structures and their functions

6. The causal circularity

- Therefore, biological and cognitive systems are something more than self-maintaining organizations operating under specific matter-energy flow conditions
- Rather, they recruit their own internal organization to actively create and maintain the internal and boundary conditions necessary for their own constitution:
- in other words, they are **autonomous systems**

7. Towards a new view of science

- For centuries biological and cognitive systems have been studied by analytic de-composition, trying to determine how their parts are arranged so as to generate an observed behavior, in a similar way as the parts in human-made machines are suitably arranged to perform an externally fixed goal
- 40 years ago Polanyi pointed out that the local rules harnessing physical (or chemical) laws, which would explain both the organization of living beings and machines, were complex sets of boundary conditions
- But where do these boundary conditions, and therefore complex organization, come from?

7. Towards a new view of science

- Darwin provided a general theoretical framework that could be used to solve this problem (or part of it). But (at least) the mechanism of natural selection requires an initial form of organization endowed with a considerable degree of complexity
- On the other hand, modern science has provided us with sophisticated computer techniques to perform quantitative studies of a wide variety of networks, showing emergent properties out of densely interconnected elements; but these theories cannot explain hierarchical organizations, articulated on multiple functional parts making up robust self-maintaining systems

7. Towards a new view of science

- Finding a theory that may eventually bridge this gap will require much more interdisciplinary collaboration in research
- The elaboration of theories and models that lead to a deeper and more global understanding of biological and cognitive systems involves the integration of very different methods and experimental data, all of them required to study even “isolated” aspects of their functioning

7. Towards a new view of science

- As it is most obviously illustrated by the research carried out on prototypical case studies or model systems (*Mycoplasma, E. Coli, slime moulds, drosophila, C. Elegans,*. . .),
- successful explanations will be achieved through the merging of models, techniques and data coming from different studies such as genomics, development, cell physiology, psychology, neurobiology, neural networks, etc.

7. Towards a new view of science

- Actually, this is the only way to combine the network-focused, holistic perspectives with the mechanistic ones
- The understanding of complex forms of holism will progressively allow (and, at the same time, will be progressively allowed by) the merging between mechanistic explanatory methodologies, based on reductionist decomposition,
- **and the construction of models (in sillico and/or in vitro)**
- Through these models it will be possible to make explicit (and interpret under new light) processes that not only give rise to those emergent mechanisms but also assemble them into coherent and adaptive wholes

Conclusion

In sum, the only way to deepen our understanding of biological and cognitive systems is developing research programs aiming at synthetic re-constructions of living and cognitive systems

- Biology and cognitive science seem to be at a historical crossroads in which the fabrication and simulation of life-like and cognitive-like systems (or subsystems) is beginning to be feasible
- The consequences of this are beyond our imagination, but we are probably witnessing the first steps of a new scientific era