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The Science of Complex Systems for Preparing the New Generation to Tackle Global Challenges

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Abstract
The contemporary Information and Communication Technologies and always faster means of transport facilitate the interconnection among the humans on Earth as never before. There is the awareness that every human is a node of a giant network, which is the humanity on Earth. A problem in a community might easily become a global issue and involve everyone living on the planet Earth. A challenge in a specific sector can have repercussions in other areas. If humanity wants to face global challenges more easily, it is necessary that higher education prepares not only specialists, but also generalists. This work proposes a strategy to form a new generation of generalists. Our strategy is based on teaching the science of Complex Systems. Complexity Science prepares a class of generalists who have the necessary knowledge and thinking skills to face any global challenge of this century.

Keywords: *Complexity Science; Generalists; Interdisciplinarity; Systems Thinking; Sustainability; Natural Computing.*

1. Introduction

A major goal of Higher Education is to prepare the new generations to tackle the global challenges of this new century. These challenges are global because they involve everyone on Earth from both the health and economic and social and ethical points of view (UN General Assembly, 2015) (Harari, 2018) (Martin, 2007). Examples are (1) the COVID-19 pandemic that affects not only physical health but also mental health, social lives, and economic activities; (2) the poverty in the world, which favors social unrest, uncontrolled migration, and wars; (3) the productive activities must transform from linear to circular, turning goods at the end of their service life into resources for others, minimizing waste (Stahel, 2016); (4) manufacturing processes and all other human activities should not perturb the fragile stability of natural ecosystems (Williams at al., 2017); (5) the warming of our planet should be curbed.

All these global challenges regard Complex Systems that are human beings, their societies, the world economy, the natural and urban ecosystems, and the climate of the Earth. Seemingly, such Complex Systems are diverse. Well-distinct disciplines traditionally investigate them: Medicine, Biology, Psychology, Social Sciences, Economy, Ecology, Engineering, Physics, Chemistry, et cetera. Such disciplinary fields are usually taught separately in higher education. The consequence of monodisciplinary teaching is that we prepare specialists who are not endowed with the required knowledge and skills to face the global challenges of this century.

It is urgent to form professional figures who know the concepts and methodologies valuable to face global challenges. Such new figures are called either polymath (Ahmed, 2019) or generalist (Epstein, 2019) or hybrid (Dominici, 2020). In our view, the minds of the young polymaths should be formed by teaching them Complexity Science (Mitchell, 2009) (Homer-Dixon, 2011) (Gentili, 2018a). Complexity Science is an interdisciplinary domain of research outlining the phenomenology and laws of Complex Systems and giving the thinking skills to tackle global challenges. In section 2 of this paper, we highlight the features of those Complex Systems that have been aforementioned and are the targets of the 2030 Agenda (UN General Assembly, 2015). We propose the fundamental theories to understanding Natural Complexity from an ontological perspective. In section 3, we point out the difficulties we encounter in describing and predicting the behaviour of Complex Systems. In other words, we present Natural Complexity from an epistemological point of view. The limitations we experience in predicting Complex Systems make the technologies that modify them highly disputable. Cumbersome ethical issues arise, as explained in section 4. Therefore, the new generations should be formed not only technically but also ethically. Finally, in section 5, we propose what we consider to be fundamental thinking skills to deal with Complex Systems. This work suggests a Higher Education path for preparing the new generations to generalists.

2. The theories for describing Complex Systems

Complex Systems as diverse as living beings, ecosystems, human societies, world economy, and climate share some features (Gentili, 2018a).

First of all, all Complex Systems can be described as networks (Mitchell, 2009), whose constitutive elements are nodes and links. The nodes are the essential elements of the network, whereas the links represent the relationships among the nodes (Newman, 2010). Nodes and links are often diverse and even variable in their behavior. The relationships are usually mutual. Furthermore, the states of the nodes affect the links and vice versa. Networks are characterized by a high degree of non-linearity. Human social networks are the most complex. Their complexity has soared. The most recent innovations in Information and Communication Technologies (ICT) remarkably affect the number, types, diversity, and variability of the relationships. Such relentless ICT innovations have promoted a transition of human societies from Complexity to Hyper-Complexity (Dominici, 2019). Clearly, Network Science is one of the fundamental theories to be taught to describe Complex Systems.

Secondly, Complex Systems are always "Out-of-equilibrium" in the thermodynamic sense (Gentili, 2018a). They are dissipative structures because they constantly squander matter and energy, producing entropy discharged mainly in the surrounding environment. Out-of-equilibrium Thermodynamics is another fundamental theory to be taught.

Thirdly, Complex Systems exhibit emergent properties (Gentili, 2021). A property is emergent when it belongs to the network as a whole. It cannot be attributed to a few nodes and links but to the entire collection of nodes and relationships. Examples are the phenomena of temporal and spatial self-organization and deterministic chaos. Some of the emergent properties can be interpreted by referring to Nonlinear Dynamics (Strogatz, 1994), the third fundamental theory to be taught to prepare the new generations of polymaths.

3. The Epistemology of Complex Systems

There are emergent properties that are not fully understood and cannot be predicted. The phenomenon of life is an example. Life has many peculiar attributes. However, we do not know its origin, we are not able to obtain it from scratch (i.e., from its molecular constituents), and we cannot predict the evolution of its forms.

Why are there emergent properties that are not understood and cannot be predicted yet? There are, at least, three primary reasons (Gentili, 2018a), which outline an "Epistemological Complexity."

The first reason is related to the difficulties we encounter in describing any Complex System by using a reductionist approach. Since any Complex System is representable as a network, its description is challenging due to:

1. The number of nodes, their diversity, and behavioral variability.
2. The number of links, their diversity, and variability.
3. The sensitivity of all these features towards the context.

In social science, not all the links are measurable in quantitative terms. Moreover, their analyses might perturb them (Dominici, 2018). The emergent properties that are not understood yet have the features of the variable patterns. Variable patterns are entities or events whose recognition is made difficult by their multiple features, variability, and extreme sensitivity to the context. Examples of variable patterns are the biological species, symptoms and patterns in medical diagnosis, and social, political, and economic events. There are no universally valid and effective algorithms for recognizing variable patterns.

The second reason we find difficulties in rationalizing certain emergent properties is bound to Computational Complexity. Many of the computational problems regarding Complex Systems are solvable but intractable. Examples are scheduling, the Traveling Salesman Problem, the Schrödinger equation, machine learning, financial forecasting. According to Computational Complexity theory, all the solvable problems can be either polynomial (P) or exponential. All the polynomial problems are tractable because it is possible to determine the exact solution in a reasonable time lapse, whatever the problem's dimension is. On the other hand, the exponential problems having large dimensions are intractable because it is impossible to determine the exact solution in a reasonable time lapse, even if the fastest supercomputer in the world is employed. Such exponential problems are transformed into non-deterministic polynomial (NP) problems. After fixing an arbitrary criterion of acceptability for a solution, specific heuristic algorithms generate acceptable solutions that can be achieved in reasonable lapses of time. Meanwhile, many scientists, also drawn by one million dollars offered by the Clay Mathematics Institute in Cambridge, are trying to verify if algorithms can transform NP-problems into P-problems or if such transformation is impossible. If anyone rigorously demonstrated that the NP-problems are reducible to P-problems, Computational Complexity would melt like snow under the sun. This improbable event would not render any emergent property of Complex Systems predictable.

The predictive power of science has intrinsic limitations. A limitation concerns the microscopic world, and the Heisenberg Uncertainty principle expresses it. According to this principle, it is impossible to accurately and simultaneously determine two relevant features as position and momentum of any particle. Therefore, it is impossible to make trustable predictions of the microscopic particles' dynamics. Aware of this limitation, we might think of limiting our description of Complex Systems to the macroscopic scale. However, Complex Systems might exhibit chaotic dynamics. Any deterministic chaotic dynamic is aperiodic and extremely sensitive to the initial conditions. Since unavoidable uncertainties always taint any determination of the initial conditions, it derives that any chaotic dynamic is unpredictable in the long term by definition. The three fundamental reasons why specific emergent properties of Complex Systems are not understood and predictable, i.e., (1) Descriptive Complexity, (2) Computational Complexity, and (3) the intrinsic limitations of the predictive power of science, should be evident in the minds of all the future polymath figures.

4. Bio-ethical Complexity

The awareness of the limitations humanity encounters in describing and predicting the behavior of Complex Systems makes all those technologies that perturb and modify the spontaneous evolution of Complex Systems highly disputable. A fundamental question arises: "Is it always fair to do what technologies make doable?". Some technologies manipulate and re-engineer living species. Questions, such as "Is it fair to manipulate embryonic stem cells?", “Is it safe to promote the diffusion of Genetically Modified Organisms?” emerge. These and many other analogous questions are raised continuously, and when societies look for possible answers, they are usually polarized into “pro” vs. “contra” factions. Other bio-ethical issues generate societal polarization. For instance, some technologies can enhance human intellect and modify human physiology: “Should such techniques be allowed although they change the material essence of what any human being has been so far?”. Other subjects, generating harsh debate, concern about suffering and the end of life: “Is euthanasia fair?”, “Is it fair to pursue therapeutic obstinacy?”, “Is it fair to perform experiments with animals?”. Finally, human activities of production and consumption affect ecosystems and even climate. “How is it possible to feed the growing world population without polluting natural ecosystems?". "Is it possible to preserve natural biodiversity?". All these questions and other similar ones give rise to what can be named as “Bio-Ethical Complexity” (Gentili, 2021). Polymaths must be formed not only technically but also ethically to assure an equitable future.

5. Thinking Skills of Polymaths

Polymaths should have some thinking skills that are fundamental to facing global challenges.

The first skill is “Interdisciplinary Thinking” which is forged only through interdisciplinary education (Gentili, 2019). Unfortunately, the academic disciplines, as established in Western countries during the late 18th and 19th centuries and now settled in higher education and university structures, hamper inter-disciplinarity (Gombrich, 2018). Interdisciplinary degrees should be spread around the world.

The second skill is "Systems Thinking" that should be taught along with "Reductionist Thinking" (Capra, 1985). Reductionism focuses on details at smaller and smaller scales. At the same time, the systemic approach helps students zoom out from detailed and fragmented disciplinary contents and obtain a more holistic view of Complex Systems (Morin, 1992). Systems Thinking can be trained in different ways (Grohs, Kirk, Soledad, and Knight, 2018). Cognitive Maps, Systems Thinking Concept Map Extension (SOCME), and Geographical Information System (GIS) aid in exploring, understanding, and depicting both within-systems and cross-system interactions and in managing complex scenarios (Stella et al., 2019) (Wang et al., 2021). Alternatively, there is Service-learning. Service-learning is a teaching strategy that intentionally engages students with the complexity of communities through service activities (Menconi et al., 2020).

The third skill is "Computational Thinking" rooted in the research line of Natural Computing (Gentili, 2018a) (Gentili, 2018b). The rationale of Natural Computing is that any distinguishable state of either matter or energy can be used to encode information, and any of its transformations can be conceived as computations. Within Natural Computing, there exist two programs. In the first program, scholars exploit the physicochemical laws to make computations. Any physicochemical law describes a causal event. Any causal event can be assumed to be a computation since the causes are the inputs, the effects are the outputs, and the law governing the transformation is the algorithm of the computation. In the second program, scholars mimic the natural information systems, i.e., the cells, nervous systems, immune systems, and the societies of living beings. Scholars working in the field of Natural Computing propose (1) new algorithms and (2) new materials and architectures to compute in alternative to those employed in current electronic computers for facing Complexity from an epistemological point of view. Furthermore, they formulate new methodologies and models to understand Complex Systems from an ontological point of view.

6. Conclusions

It is urgent to form polymaths who can face global challenges. This work outlines a path for their formation. It regards three dimensions of a polymath: (1) the cognitive dimension, (2) the ethical dimension, and (3) the skills' dimension. The cognitive dimension is shaped by learning the ontology and epistemology of Complex Systems. Teaching the features shared by all those Complex Systems that are at the core of the 2030 Agenda allows understanding Natural Complexity from an ontological point of view. The concrete awareness of the limits humanity encounters in describing and predicting the behavior of Complex Systems allows knowing Natural Complexity from an epistemological point of view. The ethical dimension of a polymath is rooted in this awareness. Finally, the skills' dimension is rooted in an interdisciplinary mindset, systems thinking, and Natural Computing. Such skills are valuable to deal with the ontology and the epistemology of Natural Complexity.

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