CAUSE TO REFLECT
Thoughts & Opinion

Life’s irreducible structure: Where are we, five decades later?

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INTRODUCTION

The illustrious scientific career of Michael Polanyi, the Hungarian born scientist and polymath, encompassed topics ranging from chemical dynamics to the philosophy of science. In “Life’s Irreducible Structure,” an article he published more than five decades ago, Professor Polanyi proposed that organic life, specifically human self-conscious and rational life, could not be reduced to the physicochemical laws that he had spent a lifetime studying.[1] In this essay, I will detail his arguments, and submit that, in spite of the significant scientific advances made since the publication of his article, Professor Polanyi’s insights are still relevant. Drawing on his insights, I will also submit a contemporary conceptual framework for experimental strategies to better understand the principles underlying life processes. Since the major content of this perspective is my interpretation of Polanyi’s arguments in his seminal paper, references are provided only when other articles are sourced.

BOUNDARY CONDITIONS AS INHERENT TO LIFE

In making a machine, we harness the laws of nature at work in matter and use them collectively to serve a purpose. Polanyi refers to this process as the imposing of “boundary conditions” on physical and chemical laws. An analogous example is human communication: we impose the boundary condition of vocabulary on sounds to create words, and grammar on words to create sentences. When we examine a living organism, we observe similar boundary conditions. We can see that each cell imposes boundary conditions on physical and chemical laws operating in its constituent molecules; similarly, each organ on its cells, and the entire organism on all their organs. These boundary conditions are not defined in terms of the laws that they harness; rather they are irreducible to the lower principles on which they draw. Irreducible higher principles or boundary conditions are additional to, and do not interfere with, the laws of physics and chemistry. The lower level must leave enough indeterminate conditions for a higher principle to exert a new form of control.

The higher level cannot be derived automatically from the lower level—higher principles are always additional, not intrinsic, to lower principles. There may be several lower principles harnessed by a higher principle—and there may be more than one higher principle as we go from level to level in the hierarchy of life (e.g., reason and free choice in the boundary condition of mind). When a machine breaks down or a living organism dies, the boundary conditions cease to exist, and the underlying lower principles or physicochemical laws are released from the restrictions imposed by the boundary conditions, and go back to their unrestricted state.

The concept of boundary condition is that of dual control—in which a higher-level principle harnesses and organizes a lower-level principle. Each level imposes a boundary condition and reduces the scope of the level lower to it and harnesses the lower level to the service of the higher level. We can observe a hierarchy in life forms (Figure 1) from the lowest life forms, that is, prokaryotes and unicellular organisms imposing boundary conditions on inanimate matter and physicochemical laws to create life with the ability of self-preservation and replication, multicellular and plant life harnessing the power of single cells, animal life imposing boundary conditions on multicellular life to develop new sensorimotor functions, and ultimately human life harnessing animal and in particular brain function to develop self-conscious, rational life. In animal actions, all actions and mental activity are determined. In humans, enough indeterminacy exists in brain functions to allow a higher principle, that is, the mind, using the boundary conditions of reason and will, to restrict and control actions of the brain. Mind harnesses principles of biologic brain function to form reason and what we refer to as “free choice.” At each higher level, new laws are observed as applicable to that level of life. At each level in the
biological hierarchy, dual control exists: at the lower level as per a set of laws; at the higher level in accordance with new laws applicable to that level of life form (Figure 1).

Boundary conditions can sometimes be confused with holism. Holism is the process of the coming together of individual parts under the influence of physical and chemical forces, for example, a sufficiently dense cloud of interstellar hydrogen forming a sphere that we call a star; or carbon, hydrogen, and oxygen combining to form carbohydrates. Holism is not the same as Polanyi’s concept of irreducibility.

**DNA AS A BOUNDARY CONDITION**

DNA acts as a code because, unlike other molecules that settle into a structure of maximum stability and minimum potential energy, there is no physicochemical restriction on the possible sequences of the four nucleotides. The physical indeterminacy of the nucleotide sequences in DNA leads to the possibility for DNA to act as information. But to actually become information, other steps have to occur, which were not fully elucidated during Polanyi’s time. DNA, by its own boundary condition, acts as information to initiate and control the growth of other boundary conditions necessary to form a whole living organism. For the development of an organism, boundary conditions of DNA must lead to the formation of morphological structures with additional irreducible principles. Morphogenesis is analogous to the creation of a machine with its boundary conditions, but occurs naturally, by processes that are not fully understood—Polanyi postulated “field-like” powers to guide organismal development. How DNA can transmit these boundary conditions, or faculties such as self-consciousness that are currently unexplainable by physicochemical principles and biological laws, across generations, is also not clear.

**HAS PROGRESS IN SCIENCE PROVEN OR DISPROVEN BOUNDARY CONDITIONS?**

Molecular biology has added descriptive details to life processes, but not a clear knowledge of the “how it came to be” of life. While we understand the progression from genotype to phenotype, and embryonic development, to a far greater degree than when Polanyi wrote his viewpoint, we are still unable to reduce life to differential equations.

The process by which evolution creates these boundary conditions is also difficult to understand. According to Professor Polanyi, evolution could be considered as a progressive intensification of higher principles of life, a process in which higher levels are already present in rudimentary manifestations in lower forms of life. Successive hierarchies in life forms increase the independence of each level from its surroundings. Evolution is dependent on reproduction, and the origin of self-replication is also not easy to explain in terms of physicochemical laws.

**NETWORK SCIENCE AS A STEP TOWARD UNDERSTANDING BOUNDARY CONDITIONS**

Recent research has attempted to understand the formation of networks in various situations from cell phone connectivity to protein-protein interactions and connections between human diseases. A unique finding is preferential attachment—the larger the number of links that a node has with other nodes, the more links it subsequently “gets.” This leads to formation of “hubs”—nodes with a high number of connections compared to most nodes. This “hub” network model not only protects the network against random attacks on hubs (error tolerance), but also makes it vulnerable to targeted attacks on hubs (attack vulnerability). A similar scale-free power law is found to underlie network formation in very different types of networks such as social and biological networks. Interestingly, studies have shown that proteins interact not based on structural similarity but based on whether one protein is similar to another in terms of network connectivity. These hierarchical networks have been shown to exist in metabolic networks in multiple organisms. Network science could be a first step toward understanding the complexity of life processes—each part of a cell may organize itself into networks and then a network may form between these various networks to form a living cell. Such networks of networks may ultimately unravel the complexity of cells and of life. We could posit that inanimate molecules and the underlying physicochemical laws could lead to formation of networks between individual molecules, which reach a point when a boundary condition emerges from these interacting networks.

**UNRAVELLING LIFE’S IRREDUCIBLE STRUCTURE**

A major problem is that the need for boundary conditions creates a seeming discontinuity between inanimate matter and living beings. Polanyi offers a theoretical and practical solution: in a system of dual control, in which a higher level imposes a boundary condition on, and harnesses, a lower level, the control exercised by the higher level can be gradually reduced to a vanishing point. Since the effect of a higher principle over a lower principle can have any value down to zero, this will allow us to conceive of the continuous emergence of irreducible principles in the hierarchy of life—and give us a schema to investigate them (Figure 1). Polanyi described an oscillating process of “detailing” at the lower level and “integrating” at the higher level as a way forward to understand the boundary conditions that underlie the biology of life. In order to exemplify how this oscillating methodology of research could be applied to understand life, one could envisage studying every physicochemical process that occurs in a cell (detailing) and determine the formation of networks between every physicochemical process (integrating), to gain understanding of the emergence of a self-regulating network. Other potential approaches would be to study every physicochemical process that occurs from the fertilization of an egg to a fully developed organism, and the formation of networks of control at the level of the organ and organism. Given exponential
increases in computing power and ability to gather biologic data, these experimental designs are already possible.

In experiments, we do impose boundary conditions or restrictions on nature in order to observe nature’s behavior under those restrictive conditions—hence experimentation could lead to a biased understanding of nature. This fact must be considered when designing “detailing” studies. The study of boundary conditions should involve an “oscillation” between lower and higher levels—between detailing and integrating. Integration may be difficult to achieve in practice, and it may be beyond our current understanding. We will need to study a cell under minimal boundary conditions—with technologies such as molecular imaging that allow observing all the chemical reactions in a cell and the cell’s interactions with a changing environment.[8]

When we read a familiar language, we may think that we are interpreting the words by inspecting them visually, but in reality, we are targeting our mind at the shape of the words, not the individual letters themselves. A neuroscientist studying brain function may see the physiological changes in the brain as his subject sees a cat, but that may be just an observation of the “at” function operating in the person’s mind. This means that we need to understand the boundary condition to truly understand life’s irreducible principles. That is the key that connects the “from” to the “at” of dual-control situations such as life harnessing laws of inanimate matter or consciousness and rationality harnessing brain functions. A person seeing a cat sees the cat; a neuroscientist studying brain function may see the physiological changes in the brain as his subject sees a cat, but that may be just an observation of the “at” function operating in the person’s mind. This means that we need to understand the boundary condition to truly understand life’s irreducible principles.

Recognizing that life processes may not be reducible to physicochemical laws or even to a single biological “law,” and that there may be a hierarchy of “boundary conditions” in life forms, will lead to progress in understanding life processes. It is likely to give us the right scientific understanding of life and of human existence—even if it does not give a complete scientific understanding, it will give us a proper understanding of what is life and what constitutes a human being. It may be counterproductive and dangerous to assume that we will find a “theory of everything” and ignore these hierarchical boundary conditions. The hierarchy of life shows that universal explanations or single laws explaining all of life are not possible. Even if we elucidated biological networks, that knowledge may still not explain why they form and how they become self-regulating.

ACKNOWLEDGMENTS
The author wants to thank Mr. Joe Joseph, BA, who provided significant assistance in the creation of Figure 1 and editorial assistance with the manuscript.

CONFLICT OF INTEREST
There are no conflicts of interest to disclose.

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How to cite this article: Joseph, J. (2021). Life’s irreducible structure: Where are we, five decades later? BioEssays, 43, e2000250. https://doi.org/10.1002/bies.202000250