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Code Biology and the Problem of Emergence

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Abstract

It should now be recognized that codes are central to life and to understanding its more complex forms, including human culture. Recognizing the 'conventional' nature of codes provides solid grounds for rejecting efforts to reduce life to biochemistry and justifies according a place to semantics in life. The question I want to consider is whether this is enough. Focussing on Eigen's paradox of how a complex code could originate, I will argue that along with Barbieri's efforts to account for the origins of life based on the ribosome and then to account for the refined codes through a process of ambiguity reduction, something more is required. Barbieri has not provided an adequate account of emergence, or the basis for providing such an account. I will argue that Stanley Salthe has clarified to some extent the nature of emergence by conceptualizing it as the interpolation of new enabling constraints. Clearly, codes can be seen as enabling constraints. How this actually happens, though, is still not explained. Stuart Kauffman has grappled with this issue and shown that it radically challenges the assumptions of mainstream science going back to Newton. He has attempted to reintroduce real possibilities or potentialities into his ontology, and argued that radically new developments in nature are associated with realizing adjacent possibles. This is still not adequate. What is also involved, I will suggest, utilizing concepts developed by the French natural philosopher Gilbert Simondon, is 'transduction' as part of 'ontogenesis' of individuals in a process of 'individuation', that is, the emergence of 'individuals' from preindividual fields or milieux.

Keywords: Code biology; Emergence; Hierarchy theory; Downward causation; Final causes; Teleology; Infodynamics; Anticipatory systems; Dissipative structures; Transduction; Individuation; Marcello Barbieri; Stanley N. Salthe; Robert Rosen; Gilbert Simondon

Introduction

Recognition of the nature and role of codes in life is clearly a major advance in biology. The neo-Darwinian synthesis incorporated the notion of the genetic code. However, as originally characterized by Crick and Watson, the reproduction of DNA and RNA was understood, as Erwin Schrödinger had suggested in his influential work, *What is Life?*, as analogous to the reproduction of arrangements of molecules with the growth of a crystal. A few years later when it was found that the sequence of nucleotides in DNA determines the sequence of amino acids in proteins, the same analogy was utilized. As originally formulated, DNA produces RNA which produces proteins, and what kinds of proteins are produced are simply the effect of the order of nucleotide bases in the DNA and then the RNA with the kinds of proteins produced being determined by stereochemistry. DNA, identified with Mendelian genes, insulated from influences of the rest of the organism by the Weismann Barrier, could then explain the characteristics of phenotypes. Proteins, produced by DNA and RNA, form three dimensional structures which form living organisms. This was seen as a triumph of the bottom up, reductionist form of explanation, reducing life to nothing but arrangements of chemicals and their interactions organized in such a way that organisms have the attributes that enable them to survive and reproduce themselves more successfully than other arrangements of chemicals. Characterizing such arrangements of nucleotide bases as encoding information, incorporating information science based on the work of Claude Shannon and Norbert Wiener into biology, was not a significant challenge to this reductionism. We were left with a characterization of organisms as gene machines, or machines for reproducing DNA (or occasionally, RNA by itself).

The code biology of Marcello Barbieri shows why this neo-Darwinian synthesis has to be rejected. Proteins are not determined by stereochemistry, even in the most primitive forms of life. The bridge between genes and proteins is provided by transfer RNA that have one recognition site for a group of three nucleotides, a *codon*, and another for an amino acid. The two recognition sites are spatially separated and chemically independent and there is no necessary, chemically determined relationship between codons and amino acids. The production of proteins involves 'conventions' in the sense that which proteins are produced by RNA could be otherwise with different conventions. These are codes in the sense that there is encoding of information which is then decoded according to these conventions. This is a complex process involving a carrier of genetic information, a messenger RNA, a peptide bondmaker consisting of a piece of ribosomal RNA, and transfer RNAs that can carry both nucleotides and amino acids. This means that protein making in the most primitive life forms involves three different types of molecules: messenger, ribosomal and transfer RNAs. So, in each cell there is a 'ribonucleoprotein system' translating the genotype into proteins. Along with the genotype, the particular type of DNA which produces RNA, there also has to be a 'ribotype' (a term introduced by Barbieri), the code which is essential to determining which proteins will be produced (Barbieri, 1981). The relation between information and proteins is not dyadic but triadic. Life is in the process of translating RNA to produce proteins, not in the information encoded in the RNA (or DNA) or the proteins. Dawkins referred to genes as replicators, but this confuses the object, the genes, with the 'agent' of replication. Furthermore, there are two activities, copying and coding, with the agent being the codemaker operating between the genes and the proteins. In fact, genes do nothing. The agency is replicating and coding by the codemaker. Using the analogy of a city, such encoded information is like blueprints, and the houses are what is produced on the basis of these blueprints, with the life of the city being the process of coding and replication involved in the production of proteins. (Barbieri, 2003, 158f.)

Barbieri (2014, p.168) characterized a code as always involving 'a set of rules that establishes a correspondence between two independent worlds.' After the discovery of the genetic code, biologists discovered a whole range of codes, which although defined differently, had this feature in common. Understanding the role of codes and coding in this way introduces semantics into the most basic processes of biology, Barbieri argued. Proteins are the 'meaning' of genes for the ribonucleoprotein system of the cell, and it is by virtue of this meaning that cells reproduce themselves. The prokaryotic cell code was the first great invention that began life. Since then, there have been a series of such inventions of codes with the emergence of more complex forms of life, although each of these has not replaced the previous forms, and each new form of life presupposes and is built on the codes of earlier forms of life (Barbieri, 2008, p.31). Eukaryotic cells involved a new code, as did the development of multi-celled organisms, then animals, vertebrates, amniotes, mammals, primates and homo sapiens with the codes of language and the codes of cultures. Recognition of these diverse levels with their codes involves recognizing that each level has its own epigenesis, and this requires recognition of far greater complexity to evolution than acknowledged in the neo-Darwinian synthesis.

The biggest problem is accounting for the emergence of these codes. The first challenge is to explain the emergence of the genetic code in the most elementary forms of life, after which explaining other codes associated with the emergence of more complex organisms and living processes should be relatively easy. Trying to explain life as the product of RNA molecules reproducing themselves or catalysing the replication of other RNA molecules has been shown to be impossible because of the instability of the processes involved (Barbieri 2003, p.140f.). With qualifications, Barbieri (2003, p.131ff.) aligned himself with a different tradition going back to Alexander Oparin, arguing that metabolism came first, and examined efforts of those following Oparin such as Tibor Gánti, Stuart Kauffman and Freeman Dyson to fill out the details of how such metabolic processes could have begun

and developed. Dyson showed that such metabolisms did not have to replicate exactly and could have supported inert or parasitic molecules, including RNA molecules. It is in the context of such metabolism that RNA, initially produced as a waste with the potential to be dangerous to this metabolic process, could have taken over the metabolism to reproduce itself, as does a virus, in the process, stabilizing the process of replication of the metabolism. Barbieri rejected this for failing to acknowledge the complexity of coding and offered an alternative theory of how coding could have emerged under these conditions. His proposal (1981; 2003, p.145; 2019a) involved still accepting the metabolism first hypothesis but recognizing that primitive RNA able to catalyse peptide bonding, that is, *polymerising ribosoids*, could have been operative within this metabolism, creating a *ribotype world*. Primitive ribosoids could become protoribosomes. While far more promising than the alternatives, accounting for the emergence of the complex ordering involved in coding and replication is still a huge problem, as Barbieri has acknowledged. The code that appears to have emerged with the beginning of life, although 'conventional', is universal and has not changed during the history of life. How could this complex and highly successful code have originated? To add plausibility to his theory, Barbieri (2019b) has recently conjectured that such codes could have developed by a process of 'ambiguity reduction', allowing that the first codes were poorly defined. Even allowing this, it is still a challenge to show how the first code even in its ambiguous form could have originated.

The Reality of Emergence: Against Reductionism

In addressing this challenge, it is first necessary to consider what emergence could mean. The idea of emergence as a major feature of evolution had been developed and strongly defended in the first decades of the Twentieth Century, most importantly, by Henri Bergson, Samuel Alexander, Conwy Lloyd Morgan and C.D. Broad (Blitz, 1992). These philosophers influenced Alfred North Whitehead (Gare, 2002), who in turn was a major influence on the theoretical biology movement, particularly the work of C.H. Waddington (Griffiths & Stotz, 2018). As the leading figure in this theoretical biology movement, Waddington's career culminated in the organization of four major conferences on theoretical biology in Belagio, Italy, beginning in 1966. The proceedings of these were edited by him and published in four volumes as *Toward a Theoretical Biology* (Waddington, 1968-72). Influenced by Whitehead's concept of concrescence, Waddington developed the notion of 'chreod', canalized paths of development in the epigenesis of embryos, and also, in cognition. These developmental paths engender form (morphogenesis), differentiation of cells and regionalization, that is, the individuation of the components of the organism. Chreods are only comprehensible as emergent processes. The participants in these conferences, who included Brian Goodwin, Howard Pattee and Stuart Kauffman, defended versions of evolution involving the emergence of multiple levels of organization irreducible to each other and interacting with each other.

However, as David Blitz (1992, p.147ff.) showed, the whole idea of emergence had been opposed, firstly, by Bertrand Russell, and then by the logical positivists who effectively equated science with reductionist explanations. They also ruled out any role for natural philosophy in scientific research through which implicit ontological assumptions could be questioned. Mainstream biologists embraced logical positivist reductionism, further legitimated by the achievements of molecular biology and information science. Reductionism in biology is the commitment to always looking for explanations from the bottom up, searching for interactions between components to explain macrophenomena, including compound individuals and their behaviour. The challenge is to show that macrophenomena are simply the effects of the interactions between components. This is the physicalist thesis according to which life is chemistry and chemistry is physics, and the most important branch of physics is elementary particle theory (or string theory). Any appearance of new kinds of beings with new

attributes are just that; appearances that can be explained by the most basic kind of entities in nature, whether these be elementary particles or strings. While it is convenient to use language which characterizes macrophenomena and their properties, this language should be taken as shorthand for what ultimately can be understood as purely physical processes that with enough work, could replace this shorthand language. The ultimate goal of science is to produce a mathematical model of the entire universe through which everything that has existed, does exist and will exist can be explained as manifestations of the activities of elementary particles with their fields, or strings, and their interactions.

The theoretical biologists, despite their arguments against logical positivism and success at pointing to the limits of reductionist explanations, were marginalized, and biology is still dominated by this reductionism. Reductionism is identified with genuine science, and so most biologists do not acknowledge that there could be emergence, despite more work on the extended evolutionary synthesis revealing more clearly the causal efficacy of emergent levels of biological organization actively constraining lower levels, and even constructing niches to develop their components (Jablonka & Lamb, 2014; Sukhoverkhov & Gontier, 2021; Stotz, 2017). Biosemioticians influenced by C.S. Peirce also rejected logical positivism and the reductionism of the molecular biologists and information scientists, and have given a place to diverse levels of organization and their emergence. Jesper Hoffmeyer (2008) introduced the notion of scaffolding whereby relations are responded to, characterizing emergence through such scaffolding, and Kalevi Kull (2009) examined the semiotic thresholds between vegetative, animal and cultural semiosis. However, many Peircian biosemioticians have been disinclined to face the biggest challenge to theories of emergence, the origin of semiosis, because of the influence of Peirce's suggestion that semiosis is ubiquitous. Consequently, the first instance of semiosis does not itself need to be explained.

The problem with reductionism is that in searching for explanations its proponents are always assuming the existence of complex individuals and their behaviour or processes that themselves are in need of explanation. Barbieri (2012) has recognized this. He has pointed out that information, along with heredity and natural selection, do not exist in the world of chemistry. Neither does 'organic meaning' as he has defined it through code biology. However, to clarify these claims it is necessary to recognize that emergence is more ubiquitous than Barbieri acknowledges. This can be illustrated by a purely and straightforwardly physical entity, a gas. If one molecule, or even a small number of molecules, is introduced into the vacuum within a container, it is not a gas with the properties of a gas, such as pressure and temperature and a relationship between them. However, with enough molecules there is a gas and has to be acknowledged as such, with not only temperature and pressure and a direct relationship between them, but with properties such as the potential to transmit sound waves. With a gas, a new existent has come into being, and even when studying its powers and liabilities and analysing how these are possible through studying its components, analysis presupposes the reality of the gas being explained. 'Temperature' and 'pressure' do not have any meaning when focussing on individual molecules and their particular interactions, but they are clearly real phenomena, as is the mathematically expressible relation between them. They do not exist at a point or at an instant, but only in a volume and over a duration. None of the properties of a gas can be characterized by describing molecules by themselves, or by looking at the particular interactions between them. Pressure and temperature emerge as properties of an emergent entity consisting of a large number of molecules interacting in an environment that functions in some sense as a container for this entity. With the container, it is also necessary to acknowledge volume which also is related in a mathematically expressible way to pressure and temperature. This 'container' could be the Earth, separate from other celestial bodies, with gravity keeping the gas (the atmosphere) in place.

Emergence is more complex with living beings, but the same principles apply. In examining an emergent entity, there is always a tendency to smuggle in some notion of what it is and to assume its existence prior to the description of how it came into being and how it functions. With living beings, final causes are essential to what is being studied. As Michael Polanyi (1969, chap.14) pointed out, mechanistic explanations tacitly assume the function being served by what is identified as a mechanism, and function implies a final cause. The assumed final cause is a form of tacit knowledge, and for this reason can be denied. However, even when being denied, this tacit knowledge tends to manifest itself, as for instance when Richard Dawkins, the arch-reductionist, speaks of genes as cunning, intelligent agents able to control vast complexes of chemicals. Recognition of a telos to life is fairly obvious when identifying codes, but a telos is tacitly recognized even when identifying chemical interactions as a metabolism since doing so presupposes that they are serving a function in utilizing and transforming useful energy to serve the maintenance and reproduction of this process. There must be an individual of some kind for these chemical reactions to serve as a function. Accepting Oparin's claims, the most primitive living beings were interacting chemicals that aggregated in a way that is capable of weak metabolism, forming a metabolic system that even before the development of polymerising ribosoids was able to replicate itself, although not exactly. Oparin was identifying this as a metabolic system, but it is only as part of a living being that it can be identified as a metabolic system.

What is involved in tacitly accepting the reality of an individual and its causal efficacy can be clarified further by looking at a case where it was first denied and has been subsequently recognized. This also shows the efficacy of downward causation. Denis Noble began his career as a card-carrying reductionist. With colleagues he constructed the first satisfactory virtual model of a functioning heart. He realized that in this model there is not a separate oscillator that controls the pacemaker, but that regulation is an emergent property of the feedback loops. As he put it:

If you isolated all the components, there would be no oscillator. Yet each differential equation describing any one of those components would be just the same. What would change are the constraints provided by the cell itself when those components are part of a living cell.

Constraints? Where do those appear in any differential equations? They arise from a necessary mathematical fact: the equations have no solution unless you specify the initial and boundary conditions. Those form the constraints in such a mathematical model. They arise from the organisation of the higher level. The principle therefore achieves two necessary criteria: no privileged level of causation, and the top-down form (the constraint) is just as necessary as the mechanical upward form. The top-down causation is attributable to formal organisation, within which the bottom-up dynamic causation is constrained to occur. (Noble 2021, p.15)

This is similar to the entrainment of individual alternating-current generators in a national electrical power grid. A virtual governor emerges which controls the entire system, even though it has no palpable or locatable physical existence. Such mutual entrainment of oscillations and their effects have been used to develop much more complex control systems designed to achieve generalized optimal-superadaptive control. This is a function, and as such, implies a telos. As a non-localized form of downward causation, such control has been used by Dewan (1976), not only as a model of the functions of organisms, but how the mind emerges and how it functions.

That apparently reductionist explanations presuppose boundary conditions, and that these boundary conditions function as holistic constraints and thereby as a form of downward causation, had earlier been observed by Howard Pattee (who was influenced by Polanyi) and Stanley N. Salthe (who in turn was influenced by Pattee). Initially concerned to analyse the nature of control in organisms, Pattee advanced Polanyi's hierarchical ontology by developing the notion of non-holonomic constraints, showing in this way how matter can become a symbol and as such, function as a controlling constraint. Such constraints open new possibilities for organization. As Pattee (1973, 73f.) argued:

The constraints of the genetic code on ordinary chemistry make possible the diversity of living forms. At the next level, the additional constraints of genetic suppressors make possible the integrated development of functional organs and multi-cellular individuals. At the highest levels of control we know that legal constraints are necessary to establish a free society, and constraints of spelling and syntax are prerequisites for free expression of thought.

Salthe took up Pattee's work and developed it further, explicitly relating it to biosemiotics and using it to characterize emergence. He argued that such emergence occurs through the interpolation of new constraints.

Part of the problem with the view of emergence through constraints is that it assumes that fractionated components exist self-sufficiently and are somehow constrained to form part of the emergent system. This is associated with a tendency to see emergent entities as supervening over smaller entities, ignoring the environment in which these entities were able to exist in the first place, and then the new environment created by the emergent system. Salthe corrected this view, pointing out that emergence, in both evolution and development, is associated with interpolation between processes of larger and smaller extensions and slower and faster rate processes, modifying both the larger and the smaller processes. Granting a place to scalar hierarchies was then used to characterize and explain final causes. As Salthe observed: 'constraints from the higher level not only help to select the lower level-trajectory but also pull it into its future at the same time. Top-down causality is a form of final causality' (Salthe 1993, p.270).

Thermodynamics, Hierarchy, Heterarchy and Life

This leaves the problem of accounting for why new constraints should have been interpolated, including those associated with life. To explain this, Salthe (2005; 2018) invoked thermodynamics and the universal drive to eliminate energy gradients to achieve equilibrium, transforming 'useful' energy (negentropy or exergy) into entropy. He aligned himself with the work of Ilya Prigogine (1988; 1996) who speculated on how the universe began not from a singularity but from the instability of the vacuum, which resulted in the creation of matter, and argued that this is all part of the process of eliminating energy gradients which is the broadest final cause in the universe and the condition for all other final causes. As Ilya Prigogine and his colleagues (Prigogine, 1976; Nicolis and Prigogine, 1989) showed, far from equilibrium systems generate dissipative structures in which fluctuations are amplified to generate long-range correlations and spatially ordered patterns, facilitating the move towards equilibrium in place of haphazard diffusion. From Salthe's perspective (2003; 2005), dissipative structures and the ordered patterns generated are emergent constraints interpolated between the system as a whole and the components of these structures which are constrained by them. Structures increase the rate at which systems move towards equilibrium and their maintenance is dependent upon continual inputs of exergy. However, intense dissipation processes produce forms

of exergy that cannot be utilized by such processes, and different structures are generated to utilize these forms of exergy. In such cases, informational constraints develop which delay energy dissipation so that energy is dissipated more completely. These are associated with what Jørgensen (2001) proposed as a Fourth Law of thermodynamics, that in order to extend potential for dissipation and to explore pathways for achieving this, a system will tend to a maximum of stored energy to maximize its exergy mobilization potential. Howard Odum suggested that this would be associated with gross energy flows through the system increasing at a decreasing rate until it reaches maturity.

Nicolas and Prigogine (1989, p.31ff.) argued that living beings are special kinds of dissipative structures involving the generations of functional forms, including 'memory' of forms and functions acquired in the past, facilitating more effective elimination of energy gradients. Their dynamics are constrained not only by boundary conditions, but also by information (including genetic information) associated with such memory. Accepting this, Salthe (2005) also argued that living beings are organized to maintain energy gradients and to maximise their exergy mobilization potential. They are also organized to insulate their components from the more intense dissipative processes and from weaker energy gradients that they cannot utilize and so must be disposed of as wastes, while at the same time organized to uncover previously inaccessible energy gradients to exploit. Salthe argued that final causes, as with the reduction of energy gradients by hurricanes or by a flame, should not be identified with purposes. He accepted that as a final cause such transformation of energy is only 'teleomaty'. However, with life the organization of energy transformations serves the end of the maintenance, development and growth of the organism, and organization to realize these ends is a defining feature of life. The most basic form of this he characterized as 'teleonomy'. Where more complex forms of life are associated with the development of awareness of ends, final causes can be characterized as 'teleology'.

These processes of life involving diverse but integrated forms coordinating and being coordinated in their activities. As Salthe (1993; 2012a) and then Alicia Juaerro (1999, chap.9) argued, building on the work of Pattee, they are characterized by compositional hierarchies of enabling constraints. These enabling constraints do not always determine the activities of their components but rather harness these components by facilitating a range of activities by these components which then serve and reproduce the wholes of which they are part, while the forms created through their activities are able to engage in more complex activities and serve larger forms again. Salthe characterized the different levels primarily, although not always, through scales, although as Brian Goodwin (1963) (building on the work of C.H. Waddington) argued, and O'Neill et.al (1986, p.86) concluded through the study of ecosystems, hierarchies can also be differentiated by process rates. Salthe (2012b, p.598) did consider different process rates when examining the role of information in the regulation by higher levels of lower level systems in which information functions as signs. Signs must endure to mediate between different scales, both in material size and temporally, dealing with different rates of activity. However, this observation was not developed.

Salthe concluded that scalar or compositional hierarchies do not identify the different kinds of beings - physical, chemical, biological or psychological, however. He argued that there are also specification hierarchies where broader classes subsume sub-classes such that the broader class has all the properties of the sub-class, but the sub-class has properties specific to it not shared by all members of the broader class. Thus, conscious beings are a sub-class of biological beings and biological beings a sub-class of physical beings. This still leaves the problem of identifying what differentiates the different kinds of beings specified in this specification hierarchy. If scalar hierarchies cannot account for the difference between non-living and living beings, how is it possible to account for the difference apart from acknowledging the obvious, that they are different? And why should living

beings be singled out as worth classifying as a sub-class? Salthe grappled with this problem, integrating the work of a diversity of thinkers (1993, p.52ff.). Different degrees of integration, individuation, generative development and levels were acknowledged as some of the rules for making such specifications (p.64f.). Higher levels were seen as dependent on lower levels, but not vice-versa.

The most important development of Salthe's work on this topic has been associated with his effort to characterize these hierarchies through 'informational constraints', integrating 'infodynamics' and Peircian semiotics (Salthe, 2003; Salthe & Fuhrman, 2005; Salthe, 2012c). Infodynamics as developed by Salthe involved accepting a deep connection between Boltzmann's statistical interpretation of physical entropy and Shannon's formulation of variety as informational entropy, claiming that such information can be associated with meaning when it acts as a constraint on entropy production (Salthe, 1993, p.105; 2003; 2008, p.134ff.). On this basis, he defended pansemiosis, ascribing a proto-semantics to all information so conceived to allow full semantics to emerge with complex forms of life. However, it has not been demonstrated that Shannon's notion of information by itself, apart from being a precondition for any form of messaging, has much relevance to understanding biosemiotics or is adequate to characterize the semiosis of living organisms, and efforts in this direction have been strongly challenged by biosemioticians (Gare, 2020). The ascription of meaning to Shannon information had already been rejected by Shannon and Weaver (1949, p.8), warning: 'The word information, in this theory, is used in a special sense that must not be confused with its ordinary usage. In particular, information must not be confused with meaning.' While Salthe argued that information becomes a semiotic concepts when it is a constraint on entropy production, information in this sense is not Shannon information, and conceived as a constraint in this way only makes sense in relation to the functioning of organisms. Relating information as signs functioning as constraints to processes related through different rates of activity was promising, but as noted, this idea was not fully developed by Salthe. Without the relationship between Shannon information, information as it originally had been understood as the process of in-forming living beings, and information conveyed by signs being better worked out, Salthe's specification hierarchy remains as a classificatory scheme with only partial explanations for what is distinctive about different forms and levels of life.

The work of Robert Rosen provides some basis for clarifying the nature of this specification hierarchy. Rosen worked with Pattee in developing hierarchy theory, but became dissatisfied with his inability to characterize what he referred to as 'life itself'. Rosen was a biomathematician involved in the development of Category Theory, and argued that just as through Category Theory it is possible to model one branch of mathematics by another, it is possible to model causal entailments in the world, and this in fact defines the goal of true science. Following John von Neumann, he argued that living beings must have models of themselves, and building on Category Theory set out to model such systems. These systems are organized not merely hierarchically, but also consist of processes that are components of each other without being reducible to each other. They are in heterarchical relation. Rosen's work does not require the rejection of hierarchy theory, and is compatible with Salthe's account of final causes associated with downward causation, but adds a new dimension to it. Systems with models of themselves are able to repair themselves, and if they can repair themselves, they are capable of reproducing themselves. Rosen claimed that with advances in mathematics able to model such relations, 'Why?' questions can now be asked and functions can be accorded a place in biology, and understood as such. This is associated with a stronger notion of final causes than that living beings reduce energy gradients, or that, through feedback mechanisms, organisms reproduce themselves. While life develops as a special kind of dissipative structure for degrading energy gradients, by virtue of the reflexivity associated with organisms having models of themselves, the means become the end: to perpetuate life. This is only possible by accessing and degrading energy gradients, but with life, accessing and transforming exergy is the means for survival, development, growth and reproduction.

Criticising the haphazard way in which analyses had been performed in reductionist approaches to biology where it is simply assumed that the components of analyses will be fractionated components, Rosen argued that functions cannot be simply identified with fractionated components. It is important to appreciate that for Rosen, models are not to be identified with fractionated components but are a feature of the whole system in the context of its environment. The action of models is first of all a form of downward causation, just as the virtual governor of the national power grid with no palpable or locatable physical existence regulates the entire system. It is through such models that organisms differentiate themselves from their ambience and maintain this differentiation and control interactions between themselves their ambient environments, anticipating the future and modifying themselves or acting in response to what is anticipated. Living beings are anticipatory systems.

Rosen's work has played an important role in freeing scientists from deep assumptions deriving from the success of the Newtonian model of science (influenced by Descartes), most importantly, that there can be no place for purpose in the physical world, and if there appears to be purposeful behaviour, it should be regarded as nothing but an appearance to be explained away by invoking chance variation and selection, or feedback mechanisms facilitating survival. Also, in challenging and rejecting the identification of functions with fractionated components, Rosen freed science to do full justice to the reality of functions and purpose, and to appreciate that these need not be localized at some place within the system being studied. As such, they are more than shorthand for describing how things are, as though it would not be essentially different from holding that the function of the bottom of a mountain is to hold up the top of a mountain. Functions and purposes in life have an irreducible ontological status while only existing through the physical processes from which organisms are composed. This is an important argument against Descartes' defence of ontological dualism on the grounds that the mind, unlike extended matter as represented by analytic geometry, is not localized and divisible, and so cannot be a physical being.

However, there are several problems with Rosen's work. One, which I have dealt with elsewhere (Gare, 2019), is to have conceived Newtonian science as mechanistic, and counterposed his own mathematical models with mechanistic models, characterizing mechanistic models by their ability to subsume all particular models under a general model from which these particular models can be derived. In fact, mechanistic models are not only compatible with the view of anticipatory systems characterized by functions and purpose as modelled by Rosen, but presuppose such functions and purposes. Mechanisms by their very nature, as Polanyi argued, are only mechanisms insofar as they serve some purpose. It is only in relation to such purposes that the organization of their material components can be understood. The organization of a car, for instance, cannot be understood through physics and chemistry, and the same is true of a heart. This does not mean that Rosen was wrong to oppose the identification of life with complex machines, assuming that if we can develop a sufficiently complex machine we would be justified in equating it with a living being. Mechanisms presuppose life, and life is not just a complex mechanism or a collection of complex mechanisms, and without life, there would be no mechanisms. If there is no life on Venus, there are no mechanisms on Venus. Mechanistic explanations can only be a part of science.

This raises a second problem, considering the relationship between holistic, downward causation associated with organisms having models of themselves and the functioning of mechanisms, which is also related to the question of the relationship between Rosen's earlier work on hierarchy theory aligned with Pattee and his later work (Pattee 2007; Gare 2013). Rosen was centrally concerned with the capacity of organisms to repair themselves, but characterized this at a very abstract level, particularly in his later work. In practice, DNA replication which is a localized process is an extremely important mechanism for such repair, leading reductionists to ignore everything else. However, even

with the double helix stabilizing strands of DNA, this is not stable enough by itself, and it has been argued that proof-correcting machinery is required to reduce the error rate in replication from 1 in 10^4 to 1 in 10^{10} (Noble 2017, p.166n26.). How this is achieved is still not fully understood, but it requires a well-organized army of proteins that work only in the context of the cell that can cut and paste and move DNA around, correcting hundreds of thousands of mistakes without a single error (Noble 2021, p.11). Such error correcting involves the whole cell, and there is no separate replicator from the 'vehicle', and involves analogue information as well as digital information.

Beyond the Newtonian Model of Science

This raises the further problem of considering what is the relationship between functions and fractionated components, most importantly, the mechanisms that play a role in its functioning, and how could such complex relations ever have emerged. To address this problem it is necessary to question the identification of science with the mathematical modelling of entailments, leaving no place for explanations of what is not entailed. In arguing this, Rosen was not breaking sufficiently with the Newtonian model of scientific explanation. Stuart Kauffman (2000, p.123) has pointed out the problem with this. It assumes that we can produce mathematical models that pre-state all possibilities, or as he put it, 'prestate the configuration space of a biosphere', after which we can identify all possibilities actually existing and then deduce which possibilities will be realized in the future and which possibilities must have existed in the past. This leaves out contingencies leading to radically different developments involving realizing 'adjacent possibles' which are not and cannot be entailed in any mathematical model, no matter how well developed the mathematical model is. Illustrating this point, we can conjecture how lungs originated and then evolved. Fish, short of oxygen while relying on their gills, gulped air and utilized their swim bladders to compensate, setting in motion a pattern of behaviour inherited over generations leading to the development and selection of organisms with better capacity for absorbing oxygen in this way. As Kauffman argued, this is the realization of an adjacent possible and it is impossible to pre-state this possibility mathematically. To explain it, he argued, we have to fall back on stories.

From this example we can see that in defining a living organism, function has to take priority over form and structure. Structures originate and evolve to serve a function. As mechanisms or components of mechanisms, they are localized and their functioning can be explained through physics and chemistry; however, it is only because they serve a function that they can be recognized as mechanisms, and generally, they can only survive and function in the environment provided by the whole organism. The structures that have evolved with the development of these mechanisms can be captured and serve very different functions by the organism functioning as a whole with a basic final cause of staying alive, with the further final cause of eliminating energy gradients. This can even lead to new functions and new mechanisms, such as utilizing skin flaps to glide in the struggle to flee from predators or to find food, which may then lead to the evolution of wings with the mechanisms that have enable bats to fly and find totally new niches and energy gradients to exploit. Some structures can function as components of different mechanisms, as with kangaroos where hopping facilitates breathing. With the multiplication of functions and structures, coordination becomes ever more important, both between the functioning of components and in relationship to the functioning of whole organisms. As a number of theorists have argued, patterns of resonating and entrained oscillations are essential to such coordination (Goodwin, 1963) and Ho (2008). Denis Noble in *The Music of Life* (2006) and *Dance to the Tune of Life* (2017) has revived interest in this aspect of life. Ho (2008, p.81, 93 & 128) pointed out (following Herbert Fröhlich among others) that coupled cycles of such oscillations provide the capacity to store useable energy at multiple levels, and to be able to

transform energy quickly with minimum entropy production in response to specific, weak signals. This stored energy able to be utilized very quickly gives organisms autonomy from their environments. Living organisms are able to participate in evolutionary processes through which ecosystems develop as dissipative structures. These processes include the formation of symbiotic relations, modifying the physical environment including both soil and climate, achieving a competitive balance between different species and the elimination of some traits within organisms through competitive struggle for survival, these functioning as further constraints augmenting the conditions for life.

While telling a story about the realization of adjacent possibles, there is still a problem of accounting for what happens in such realization. These are not just random events. The problem is that along with rejecting the Newtonian model of science it is also necessary to abandon deeper assumptions that went along with this, the substantialist notion atomism of Newton and of formed matter and the limited notions of causation that still influence the thinking of scientists. What is wrong with this is that it presupposes completely formed individuals having an identity over time as the basis for explaining the emergence of new individuals, presupposing this identity of individuals which is the problem to be explained. Questioning atomism often leads to efforts to resurrect the matter/form distinction of Aristotelian physics, equating energy to matter and treating individuals as forms of energy. But here matter and form are still treated as already objectified and individuated causes that can somehow be brought together, and even this is a problem. Going beyond both Newton and Aristotle, Rosen provided a good characterization of the essence of life itself, but offered no account of how it could have originated, and given his identification of science with mathematical modelling, was not in a position to give a place to genuine emergence.

To overcome this problem, Prigogine (2003) argued that mathematical models are abstractions with limited applicability, and so cannot do justice to real creativity in the universe. Salthe's characterization of development and evolution based on thermodynamics and explaining the emergence of individuals as the interpolation of constraints to facilitate the better elimination of energy gradients accords with Prigogine's arguments. However, there is still a problem of showing what this interpolation involves, and when it comes to thinking about the emergence of life in all its complexity, more work is required to appreciate even the possibility of this. What is required is a re-opening of the question of what is individuation and how does it occur. Fortunately, Gilbert Simondon undertook this task in the 1950s, relating work on this topic from the pre-Socratics onwards, including the work of Schelling and Bergson, to recent developments in science, and in particular, to thermodynamics. His work is consistent with and to some extent supported and clarified by the later developments in thermodynamics by Prigogine and his colleagues, Salthe, Fröhlich and Ho. His major work, *Individuation in Light of Notions of Form and Information* (2020), ignored for decades, is now widely available.

In focussing on individuation, Simondon characterized the ontogenesis of individuals from the pre-individual to form the cosmos, to some extent, echoing Anaximander's explanation of the origin of the cosmos in the limiting of the unlimited (an idea embraced and further developed by Friedrich Schelling). While concerned with cosmogenesis, Simondon was also concerned with individuation in more limited contexts, in which case the pre-individual was equated to the environmental field or milieu of ontogenesis. He argued that there could be no principle of such individuation, since principles assume individuated elements, and it is these that have to be accounted for by ontogenesis. As such, this topic is part of natural philosophy, accounting for the possibility of science which focusses on individuated beings and their relationships to each other, at the same time revealing the limits of such science in its inability to accord a place to genuine creativity in nature. Simondon's work on

ontogenesis also aimed to provide the foundations for epistemology and ontology, while highlighting the limits of these.

To characterize such ontogenesis, Simondon took over the term 'transduction' from the genetic epistemology of Jean Piaget. In Piaget's work, transduction is distinguished from deduction and induction as the process of structuration by which young children see connections between unrelated events. It is also distinguished from the Gestalt of Gestalt psychology in always being incomplete and open to further transduction. Through this structuration, objects of perception and thought are individuated. For Simondon, such structuration is not only psychological but also social, biological and physical. The objects of perception and thought are produced from the pre-individual as components of the human organism's interaction with its environment. Simondon then generalized this notion of transduction to characterize it as first and foremost a physical process, exemplified by crystallization from metastable systems of a supersaturated solution or a supercooled liquid. Transduction in biology and then in psychology can then be portrayed as special cases. The relations associated with transduction are not merely logical relations as in deduction and induction but have a psychological, biological and physical reality, and include the relation between what is individuated and the pre-individual milieu of this individuation. As Jacques Garelli (Simondon, 2020, p.xx) characterized transduction in the Preface to *Individuation in Light of Notions of Form and Information*:

... the processes of differentiations that are deployed starting from a metastable pre-individual system, wrought with tensions, of which the individual is one of the phases of deployment. It's in this context that the notions of potential charge, oriented tensions, supersaturation, and phase-shift, borrowed from thermodynamics, and the notion of the resonance internal to systems, intervene. According to this perspective, instead of reducing ontogenesis to the dimension restricted to and derived from the genesis of the individual, it is a question of conferring onto it the vaster characteristic of the "becoming of being, that through which the being becomes insofar as it is, qua being." ... Simondon emphasizes the incompetence of the principle of identity and of the excluded middle, formed in a perspective of substantialist and identitarian logic of the individuated being in order to deal with the problematic of preindividuated being.

Individuation is never complete in this process and the individual remains related to the field of the pre-individual with its tensions and resonances, making possible further individuation, and it is a defining feature of life to maintain metastability serving as the conditions for this. Simondon (2020, p.7) differentiated regimes of individuation, including the vital, the psychic and the social, and of the vital he wrote:

... the *living being* conserves within itself an ongoing activity of individuation; it is not merely a result of individuation, like the crystal or molecule, but a theater of individuation. Furthermore, unlike that of the physical individual, the whole activity of the living being is not concentrated at its limit; in the living being there is a more complete regime of internal resonance that requires ongoing communication and that maintains a metastability, which is a condition of life. This is not the only characteristic of the living being, and the living being cannot be compared to an automaton that would maintain a certain number of equilibria or would seek compatibilities among several requirements based on a formula of a complex equilibrium composed of simpler equilibria; the living being is also a being that results from an initial individuation and amplifies this individuation, which is

something that is not done by the technical object to which cybernetic mechanism would want to functionally compare it. In the living being there is an individuation by the individual and not merely an operation resulting from an individuation completed in a single stroke, as though it were a fabrication; the living being resolves problems, not just by adapting, i.e., by modifying its relation to the milieu (like a machine is capable of doing), but by modifying itself, by inventing new internal structures, and by completely introducing itself into the axiomatic of vital problems. The living individual is a system of individuation, an individuating system, and a system that is in the midst of undergoing the process of individuating; internal resonance and the translation of self-relation into information take place in this system of the living being.

In contrast with the physical individual for which the past is radically past, even if it is in the process of growing, as with a growing crystal, a living being is 'a node of informative communication; it is a system within a system, involving within itself a mediation between two orders of magnitude.' (p.8) The development of the psyche and of cognition is a special case of such vital transductive individuation.

The Emergence of Codes

All this provides a very different perspective for comprehending the emergence of codes. The way of thinking being opposed here is exemplified by Richard Dawkins who always started with clearly identified components of living processes and examined how they could have come together to function as a machine, and then tried to show how this machine can be explained purely through chemistry and 'natural selection'. With this approach, context is ignored except insofar as it provides a source for components, for instance, as the primordial soup of chemicals that were supposedly the original conditions for life. No role is accorded to downward causation, and certainly no role is accorded to final causes. In his account of the codes and their origins, Barbieri offers good grounds for rejecting Dawkin's theory of life and evolution, but I am suggesting here that to account for the emergence of codes, the more radical questioning of reductionism and the more radical alternative ideas outlined above are required.

Barbieri has exposed the weaknesses in Dawkin's theory of the origin of life. Dawkins referred to genes as replicators, but as Barbieri pointed out, this confuses the object, the genes, with the 'agent' of replication. Furthermore, there are two activities, copying and coding, with the agent being the codemaker operating between the genes and the proteins. In fact, genes do nothing. The agency is replicating and coding by the codemaker. Furthermore, he showed the flaws in the view that such replication could have produced a metabolic system, arguing that the beginnings of this coding activity with a conventional code would have been associated with the development of metabolic processes. There is still the problem of accounting for the emergence of these codes in the first place, even in their most basic form, allowing that to begin with they would have been characterized by ambiguity before being refined.

To comprehend this, it is necessary to examine more closely the role of codes and signs in organisms. As Pattee argued, signs (or symbols) are central to control, and such control involves a hierarchy of constraints. It is not difficult to situate codes in such hierarchical order as enabling constraints, but why should such constraints be generated? And why is control so important? I have suggested that to appreciate this, it is necessary to follow Salthe and examine living beings as energetic systems eliminating energy gradients (most importantly, less intense energy gradients), a process

which needs to be understood through thermodynamics. New codes, including the genetic code, can be characterized as interpolations of new constraints, the final cause of which is the reduction of energy gradients. The peculiarity of life is that in providing the conditions for the reduction of all energy gradients, this reduction has to be slowed. Rapid elimination of energy gradients leaves less intense energy gradients that cannot be utilized by such processes. Salthe offered an explanation for this through his characterization of information and infodynamics based on Shannon's conception of information and equating this to negative entropy. However, I have suggested that he still could not adequately characterize the distinguishing characteristics of life in this way, and had to supplement his theory of cosmogenesis with a specification hierarchy without an adequate characterization of the uniqueness of what is specified by this. Rosen provided a more adequate characterization of life itself, in so doing conceptualizing a stronger notion of final causes than using up exergy, involving anticipation and goal directedness, although not necessarily conscious purpose.

To comprehend Salthe and Rosen, it is first necessary to emphasise the primary reality of processes over 'things', whether atoms, structures or forms, and this appears to be the case also with Barbieri. Coding and decoding are activities, and rather than referring to coding as a constraint, it should be thought of as constraining activity. It is this, Barbieri argued, which is the living aspect of life. That what is important in understanding life is coding understood as constraining activity is even clearer in the case of other codes. For instance, eukaryotic cells are characterized by the dynamic instability of cytoskeletal filaments, and a different set of codes and coding, the cytoskeleton codes (Barbieri, 2003, p.180). However, what is involved in such coding is immensely complex and apparently improbable, even allowing immensely long timespans to account for their emergence, and then there is still the problem of accounting for the development of the multiplicity of codes and coding processes in the limited time of the epigenesis of each organism.

There is also a deeper problem, which when addressed, goes some way to providing a solution. Identifying these activities as coding and decoding is already to assume that they are performing a function and are not just haphazard chemical reactions. That is, as Barbieri argued, they are mechanisms, and to be identified as mechanisms already presupposes that they have a function serving a living being. And as Rosen argued, life cannot be identified with a collection of mechanisms. Life is associated not only with hierarchical ordering, but control involving modelling whereby the future is anticipated and responded to, a process which involves an organism differentiating itself from its ambience or milieu and defining this in relation to itself in the present and the future. This involves processes that are in heterarchical order, being components of each other while not being reducible to each other. The modelling process is a functioning component of the organism interacting with its environment, while the organism is a component of this modelling process. Understanding this involves recognizing a stronger form of final causation than the elimination of energy gradients, and an appreciation of goals and functions. As Rosen argued, these functions cannot be identified with fractionated components. As I have suggested, however, the existence of a function can then involve harnessing and developing various structures and processes to serve these functions, and it can be legitimately claimed that such harnessing is in the service of ends. This is what appears to have happened with the development of the ribotype to control the production of proteins using RNA and then DNA to record information. However, 'information' in this context can really only be recognized as information insofar as it is serving a memory or communication function and should not be identified with Shannon's notion of information. As Anton Sukhoverkhov (2010, p.161) argued, 'memory is a system-defining and system defined principle that actively reconstructs information and processes of the systems on the basis of inherited information, and is thus constantly reconstructed by it.' That the DNA's role in this can only be understood in relation to the function it is serving for the

whole organism became clearer when it was realized that the same parts DNA molecules can be used by an organism to produce different proteins, that is, to serve as a record for different information.

This still leaves the problem of how such a being, characterized by having the final cause of perpetuating its own existence and the conditions for doing so, could come into being, and how could it have been first identified as such. This is where the fuzziness of emergence has to be acknowledged. Just as a gas with its identifiable characteristics comes into being when there are enough molecules in a volume of space without it being possible to specify exactly how many molecules are required for there to be a gas, so it is impossible to specify precisely when a range of physical and chemical forms and processes become a living being that should be appreciated as such. Yet, it is only by presupposing the reality of what has emerged that it can be studied and concepts developed to explain it. Just as the notions of and relationships between pressure and temperature of a gas presuppose the gas, so the notions of anticipation, model, code and sign along with a number of other concepts central to understanding life, including mechanisms and properly understood, information, presuppose the reality of life. The quandary is that efforts to explain the origin of life use concepts that only make sense in relation to life.

It is here that Simondon's notion of ontogenesis as individuation from the preindividual through transduction needs to be invoked. Simondon's work written in the 1950s preceded but accords with the work of Prigogine and Salthe in privileging thermodynamics as the most fundamental physical science for comprehending the universe, and the work of Waddington, Goodwin, Ho, Noble and others on the importance of oscillatory patterns and resonance in the organization of organisms. From Simondon's perspective, whatever is identified as an individual must be seen as the product of individuation through transduction from the pre-individual. These individuals are then seen as always related to the preindividual and to other co-individuated entities, and also as the conditions for further individuations. Life is a theatre of individuations characterized by resonance by which metastability is achieved and maintained within the organism, retarding the dissipation of energy while maintaining tensions and potential for further change, including internal change with further individuations (2020, p.177). It is in these terms that Simondon characterizes emergence both with the origins and evolution of life and within organisms. Emergence is ontogenesis or individuation of a range of inter-related individuals through transduction from the pre-individual, thereby partly resolving previous tensions while leaving the possibility for further emergence. That is, as Simondon put it, 'evolution is a transduction.' (p.185).

In characterizing vital individuation, Simondon pointed out that there is no reason to assume that the physical world cannot contain a high level of organization, positing instead that right from the beginning the physical world is highly organized, and that only very complex physical edifices could transmute into living beings (2020, p.168f.). The preconditions for the emergence of life would have involved pre-vital transductions associated with the dissipative structures individuating a diversity of complex chemicals and chemical reactions serving to reduce both steep, but more importantly, relatively shallow energy gradients. Arguing along similar lines, O'Neill et.al. (1986, p.112) noted, conceiving emergence in this way is not to claim that something complex emerged from a simpler order, but that new constraints emerged to decrease the complexity of a chaotic order to ensure a new metastability permitting further developments. Through transduction, oriented tensions would have been resolved with new individuations with new relations, not only to the original transindividual metastable state, but also between these individuated individuals. This would have been a proto-ecosystem. Simondon suggested that living beings would appear in this context through the suspension of the development of physical being, and that the original unit of life would have been a complete organized group rather than an isolated individual. Further individuation to the isolated

individual would involve differentiation of this unit of life from its environment while regulating interaction with this environment. What is important is that through this transduction, a process of regulation would have been individuated along with its components involving modelling by the unit of itself, effectively remembering its past, to maintain, reproduce and further develop its capacity for utilizing potential energy, and in doing so, differentiating the unit of life from its environment and storing usable energy in metastable states based on resonances to be utilized rapidly when needed.

In this theatre of individuation of the units of life, codes, utilizing previously individuated chemicals such as ribosomal RNA, would also have been individuated as part of coding mechanisms and all their components, individuating, recording and communicating information linking the present to the past and anticipating and responding to the future, using this information to create structures to develop, maintain, and reproduce its form. As Sukhoverkhov argued, information, along with memory, should only be identified as such in relation to such coding as part of living processes. It is in this way that the first code, the genetic code as described by Barbieri, would have emerged as a transduction from complex earlier dissipative structures. The genetic code made it possible to produce, maintain and develop more efficient ways of producing forms and thereby reducing energy gradients, including those of low-grade exergy, getting rid of useless energy while maximising its energy mobilization potential, while maintaining and reproducing the metastable states and forms facilitating this. Having been individuated to serve a function, it could be expected that the code's functioning would be improved upon not only by eliminating ambiguity, but also by developing mechanisms to maintain and repair or replace the structures of the most useful chemicals (most importantly, DNA) serving this function. The milieu partly created by these individuations would then have facilitated further transductions with further individuations associated with new relations between that which has been or is being individuated, and new codes, the codes described by Barbieri (2003, p.234ff.).

Conclusion

What I have tried to show in this paper is that while code biology invalidates the reductionism of orthodox biology, there is still a problem of accounting for the emergence of codes. Contributions to solving this problem provided by Pattee, Salthe, Juarrero, Rosen, Kauffman, Noble and others are important, but do not sufficiently interrogate the deepest assumptions on which modern science is based. It is necessary to draw on the more radical thinking of Simondon utilizing his notions of 'pre-individual', 'transduction', and 'individuation' to make such emergence intelligible. This involves privileging thermodynamics in science, and this finds some support in the more recent work of Ilya Prigogine and his colleagues, Salthe, and also in Ho's theoretical biology.

Such ideas require the replacement of a substance ontology by a process ontology according to which processes only exist in relation to other processes, but are to some extent immanent causes of themselves, resisting dissolution by their environments while acting as downward causes on their constituents, providing the conditions for them and channelling their development. On this view, there is no reason for granting privileged ontological status to any one scale or level of process over others. As Mark Bickhard and Donald Campbell (2000, p.341ff.) showed, arguments against the reality of emergence are based on a failure to recognize that the proponents of emergence assume a world of processes rather than 'things', with 'things' taken to have only a derivative status. Process ontology is still marginal to biology, however, despite past achievements and recent work, illustrated by the contributions to Daniel J. Nicholson and John Dupré's anthology *Everything Flows* (2018), offering a process ontology for biology.

Simondon's version of process ontology, which is even more radical, requires a major revision in thinking beyond that which Barbieri has so far countenanced. Most scientists, even when they have rejected reductionism, assume that science should be striving to provide explanations formulated in terms of clearly specified and measurable entities or aspects of entities, whatever these might be, and to believe that apart from such explanations, no other way of understanding the world is required to comprehend nature. This assumption has to be abandoned. Polanyi, Pattee, Salthe and Noble realized that such mathematical models presuppose boundary conditions which function as downward causes. Kauffman acknowledged the limits of mathematical explanation, the ultimate quest of reductionist science in this regard, granting a place to stories that give a role to contingencies. However, this leaves the problem of accounting for the responses to contingencies that are not merely random. Bergson (1911, p.50) grappled with this problem while arguing for a process ontology. However, he was not consistent in this, invoking a universal vital impetus or '*élan vital*' to explain this creativity. This is just another way of adhering to identitarian logic and leaves the problem of the incoherence of such a postulate. Piaget (1971, p.5ff.), who, like Prigogine, Ho and Simondon, read and was influenced by Bergson's defence of a process ontology, developed the concepts of his genetic epistemology at least partly to provide an alternative to this. The notion of transduction deriving from Piaget and developed by Simondon on a more physicalist and ontological basis through thermodynamics does provide a solution since it gives a place to constrained and constraining creativity.

The problem now is to achieve a psychic and socio-cultural transduction, that is, to use another language, to achieve a major Gestalt shift in the way people think generally. This involves redefining science and its relation to natural philosophy, accepting that science is based on philosophical assumptions that can be questioned, showing through natural philosophy the possibility of science and also its limits, proposing a broader conception of science and knowledge adequate to the reality of life and mind and the thinking required for this, and then recognizing this as a solution.

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