Overcoming the Newtonian paradigm: The unfinished project of theoretical biology from a Schellingian perspective

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ABSTRACT:
Defending Robert Rosen's claim that in every confrontation between physics and biology it is physics that has always had to give ground, it is shown that many of the most important advances in mathematics and physics over the last two centuries have followed from Schelling's demand for a new physics that could make the emergence of life intelligible. Consequently, while reductionism prevails in biology, many biophysicists are resolutely anti-reductionist. This history is used to identify and defend a fragmented but progressive tradition of anti-reductionist biomathematics. It is shown that the mathematico-physico-chemico morphology research program, the biosemiotics movement, and the relational biology of Rosen, although they have developed independently of each other, are built on and advance this anti-reductionist tradition of thought. It is suggested that understanding this history and its relationship to the broader history of post-Newtonian science could provide guidance for and justify both the integration of these strands and radically new work in post-reductionist biomathematics.

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1. Introduction

Theoretical biologists are intensifying their efforts to overcome reductionism in order to comprehend the reality of life. While mechanistic accounts of life were vigorously defended at the beginning of the Twentieth Century (Loeb, 1912), reductionism reached its zenith in the third quarter of the Twentieth Century with the synthetic theory of evolution embracing molecular biology, cybernetics and information theory. Evolution was equated with changes in populations of genes, identified with DNA, encoding information on how to produce survival machines to reproduce themselves. Biology was reduced to chemistry, which it was assumed would be explained by physics. Those reacting against this reductionism have revived earlier and established new anti-reductionist traditions of thought. The notions of system, complexity and semiotics are central to their work.

However, the concepts developed to overcome reductionism have been appropriated by reductionists to develop a more vigorous form of reductionism. Paul Weiss's and von Bertalanffy's notion of system was early on turned against their whole project of overcoming mechanistic thought, although those involved in doing this appear not to have understood what they were doing (von Bertalanffy 1968, 25; O'Malley and Dupré 2005; Trewavas 2006). The notion of complexity, central to anti-reductionist thinking, has fared no better. It is clear from Warren Weaver's lecture given in 1947 in which the challenge of explaining complex organized systems was first posed, that Weaver saw this as a challenge for reductionist science, not a challenge to overcome reductionism (Weaver 1948). Most complexity theorists have focused on and studied the order generated by the interaction between very large numbers of entities. This, when taken by itself, has been recognized by some as a further triumph of reductionism. Nonlinear dynamical systems are capable of representing the world as unpredictable and capable of generating macroscopic patterns; but this is at the level of appearance. The dynamics are deterministic effects of components and their interactions and would appear to rule out anything but the appearance of emergence. This is true also of the concepts used in relation to emergent phenomena. As Per Bak, a distinguished member of the Santa Fe Institute pointed out in 1994: '[W]hat is adaptability of a complex system? Since "purpose" and "rationality," and thus "learning" and "adaptability" do not really exist in deterministic dynamical system, the question should really be: which are the features of complex systems that an outside observer might interpret as adaptability?' (Bak, 1994, p.492; Gare, 2000). While biosemiotics is still resolutely anti-reductionist, efforts have been made to provide a mechanistic explanation of codes and to account for semiosis through informatics based on the purely mechanistic notion of information deriving from Claude Shannon and Weaver. Living organisms, including humans, have been reconceived as information processing cyborgs (Brier, 2008, 22 and 35ff.).

While the resultant augmented reductionism has satisfied most researchers, others have vigorously opposed this conception of life. They had good reasons for this. Reductionism implies that science itself and the quest to comprehend nature and life are impossible. Despite efforts of reductionists to naturalize epistemology, understood reductionistically, cyborgs cannot comprehend anything. Reductionism is incoherent. For an account of the more specific deficiencies and manifest failures of the reductionist assumption, see for example Kauffman (2009). The bias towards reductionism has led anti-reductionists to investigate deeper assumptions that have continually channeled working scientists back to and reinforced their reductionism, despite its radical incoherence and its pernicious influence on the broader culture (where it has underlain a revived Social Darwinism and a form of managerialism that exacerbates and even engenders so many problems that they now have a name: 'wicked problems' (Rittel and Weber, 1973). We are scarcely advanced from the crisis in science and civilization described by René Thom in 1975 where science based technology had engendered a global ecological crisis while beneath triumphant proclamations celebrating scientific progress, there was a 'manifest stagnation of scientific thought vis-à-vis the central problems affecting our knowledge of reality.' The underlying reason for this stagnation, Thom argued, was that 'science [had sunk] into a futile hope of exhaustively describing reality, while forbidding itself to "understand" it' (Aubin, 2004, 95).

Confronting the failure to overcome this situation, anti-reductionists have re-examined the Seventeenth Century Cartesian and Newtonian reconception of the very idea of inquiry and explanation and the influence of this on the subsequent history of science, a reconception that now so permeates culture that it is usually assumed without question that only reductionist explanations have any scientific validity. Exemplifying this interrogation of embedded assumptions, Stuart Kauffman observed:

> We have lived with a world view dominated by reductionism. Yet recently, S. Hawking has written an article entitled "Gödel and the End of Physics." His observations raise the possibility that we should question our foundations. Core to this is reductionism itself. In turn reductionism finds its roots in Aristotle's model of scientific explanation as deductive inference. All men are mortal. Socrates is a man. Therefore, Socrates is mortal. With Newton's laws in differential form, reductionism snaps into place, for given initial and boundary conditions, integration of those equations is exactly deduction. Aristotle's 'efficient cause' becomes mathematized as deduction (Kauffman, 2009, 1.).

In a more recent paper, 'Answering Descartes: Beyond Turing', Kauffman again pointed to and questioned the pervasive reductionist assumptions which he claimed are now crippling efforts to characterize the mind. He noted that 'Two lines of thought, one stemming from Turing himself, the other from none other than Bertrand Russell, have led to the dominant view that the human mind arises as some kind of vast network of logical gates, or classical physics "consciousness neurons"' (Kauffman 2012, 1). On this view, the mind-brain system is nothing but 'a network of classical physics neurons, with continuous variables, and continuous time, interacting in classical physics causal ways via action potentials, vast networks with classical physics inputs and outputs' (Kauffman 2012, 3).

However, a more thoroughgoing examination of reductionist assumptions bequeathed by the Seventeenth Century scientific revolution had already been undertaken by the mathematician and theoretical biologist, Robert Rosen. Rosen observed:

> [T]he central concept of Newtonian mechanics, from which all others flow as corollaries or collaterals, is the concept of state, and with it, the effective introduction of recursion as the basic underpinning of science itself. … Thus, in my view, the *Principia* ultimately mandated thereby the most profound changes in the concept of Natural Law itself; in some ways a sharpening but in deeper ways, by imposing the most severe restrictions and limitations upon it (Rosen 1991, 89f.)

The concept of an atom did not emerge from any analysis offered by Newton; rather, he simply presupposed particles without structure and devoted himself entirely to synthesis, asking what behaviour can be manifested by such particles, individually or collectively. The formalism based on this procedure assumes that that almost everything of importance is unentailed. There is no place for final causes. Why? questions are ruled out. The only entailment is a recursive rule governing state succession. Causation is collapsed down to what can be encoded in a state transition sequence, as this is all the Newtonian language allows to be decoded back into causal language. Further strictures follow from the assumption that the universe is composed of structureless particles, that every system has a largest model from which every other model can be effectively abstracted by purely formal means, and 'this largest model is of an essentially syntactic nature, in that structureless, unanalyzable elements (the particles) are pushed around by mandated rules of entailment that are themselves beyond the reach of entailment' (Rosen 1991, 103).[1] On the basis of this analysis of Newtonian science, Rosen defined a natural system as mechanical if it has a largest model, consisting of a set of states, and a recursion rule entailing subsequent states from the present states, and every other state of it can be deduced from the largest one by formal means. On this

[1] It is important to note that field theory, which Rosen does not discuss, broke with this way of thinking in the Nineteenth Century.

basis, Rosen argued that the idea that nature is governed by mathematical laws as conceived by Newton 'boils down to the assertion that *every natural system is a mechanism*' (Rosen 1991, 103).[2]

Reductionism prevails not only because objective, scientific knowledge has come to be identified by most people with knowledge based on these Newtonian assumptions, but because these assumptions are entrenched in the way all other facets of culture are interpreted and are embodied in modern technology. Hilbert's formalism in mathematics, for instance, still widely assumed despite having been refuted by Gödel, eliminates reference to an extra symbolic reality and reduces mathematics to the manipulation of symbols. As Rosen wrote of the implications of this: 'Once inside such a universe … we cannot get out again, because all the original external *referents* have presumably been pulled inside with us. The thesis in effect assures us that we never *need* to get outside again, that all referents have indeed been internalised in a purely syntactical form' (Rosen, 1999, 77). It appears that people in Western culture (which dominates the world) are now enclosed in worlds constructed on the assumptions of classical physics that channel how they live, perceive and think, blinkering them to the reality of anything that cannot be comprehended from this physically embodied perspective. Illustrating this, in a short piece on 'Cells as Computation' published in *Nature*, the authors argued that current computer science now can provide the abstractions required for a scientific understanding of life (Regev and Shapiro, 2002). That is, the abstractions, tools and methods used to study computer systems that are built on and embody Newtonian assumptions (Rosen, 1996, 211; MacLennan, 2004; Simeonov, 2011) are now being claimed to provide the basis for integrating all our knowledge of biomolecular systems. Acceptance of this argument would completely entrench current computer science with its reductionist, Newtonian assumptions as the measure of science and so would rule out challenges to these assumptions, only allowing those aspects of life that could be comprehended through these digital computers to be acknowledged as actual and of any scientific importance.

A number of strategies have been adopted in the quest to expose, put in question and overcome these assumptions. Kauffman has taken a not uncommon path and invoked quantum theory where deeply held assumptions have been shown to be untenable. While this opens new avenues for reconceptualizing the nature of explanation and of physical existence itself which are more promising for comprehending rather than explaining away life, an alternative path is to consider what is involved in being alive, conceptualizing this, and then developing forms of mathematics and explanations appropriate to this. This path has been taken by Kauffman also, but it was embraced more resolutely by Rosen and those inspired by him. These strategies are not mutually exclusive as they can lead to the same or similar results with the development of quantum theory and the study of life illuminating each other, and as I will argue below, originated in the same anti-mechanist tradition of thought.[3] However, here it is the second path that I will focus upon, although I will suggest that in breaking down entrenched assumptions and freeing physics from mechanistic metaphysics, developments in theoretical physics are relevant to biology.

There are good reasons for taking the second approach very seriously. As Rosen pointed out in a *Festschrift* for the theoretical physicist David Bohm: 'In every confrontation between universal physics and special biology, it is physics which has always had to give ground' (Rosen 1987, p.315). Rosen's work was distinguished by a determination to develop mathematical models adequate to life as it appears to us, rather than imposing a research program coming from the physical sciences onto biology. While steadily

[2] It is also important to note that Newton himself had a more complex understanding of his mechanics than his 'Newtonian' followers and was in fact closer to the critics of Newtonianism than the Newtonians (McMullin, 1978).

[3] The biophysicist Marco Bischof has provided the history of the relationship between biology and post-mechanistic physics (Bischof, 2003). Mae-Wan Ho has attempted to integrate advances in post-mechanistic physics with the work of the theoretical biologists (Ho, 2008).

gaining recognition, his work was unfinished. He produced a trilogy, the first book of which, *Fundamentals of Measurement and Representation of Natural Systems,* grappled with the problem of measurement and representation, the second, *Anticipatory Systems,* with anticipatory systems, and the third, titled *Life Itself,* with epistemological issues raised by the effort to comprehend life (Rosen, 1978; 1991; 2012). The projected fourth work was supposed to deal with ontology, His *Essays on Life Itself* (Louie 2009, p.xiii; Rosen, 1999), published posthumously, was not this volume.

Rosen was not alone in his determination to develop a mathematics and ontology adequate to the reality of life. His own work was inspired by the relational biology of Nicolas Rashevsky and the systems theory of Ludwig von Bertalanffy (Rosen, 2006). Rashevsky, the founder of Mathematical Biophysics, developed a new approach to life by focusing on the principle which governs organization of living organisms, expressing their biological unity, independently of its material instantiation (Rosen, 1991, 117ff.). Von Bertalanffy's systems theory was developed to replace reductionist materialism and provide the foundation for a holistic conception of life. Both were concerned to apply mathematics to biology. Biologists associated with the theoretical biology movement, most importantly C.H. Waddington, were influenced by Alfred North Whitehead, who while being primarily concerned with mathematics, developed an anti-reductionist metaphysics based on an ontology of events and organisms. Although Waddington saw his own mathematical abilities as limited, he also was committed to applying mathematics to biology, and René Thom and Brian Goodwin subsequently attempted to develop new forms of mathematics to advance Waddington's ideas. More recently, biosemioticians such as Thomas Sebeok, Jesper Hoffmeyer and Kalevi Kull, embracing the work of Jacob von Uexküll, C.S. Peirce and Gregory Bateson, have also taken the experience of life as their reference point for developing their theories of life, challenging physics in the process. While being more skeptical of the potential of mathematics in this (Hoffmeyer, 1996, 38), some biosemioticians have embraced the work of H.H. Pattee (Salthe, 1993), and in one case, the work of Nils Baas, to advance their ideas (Baas and Emmeche 1996). While all this work can be regarded as complementary and efforts are being made to integrate these different research programs, along with a number of other allied or parallel developments in theoretical biology (Bischof, 2003; Letelier et.al., 2011), this is research in progress rather than a completed program.

As noted, Rosen did not produce his projected fourth volume. His student, A.H. Louie has advanced Rosen's work, but even his book *More Than Life Itself* makes no claims to providing the ontology promised by Rosen (Louie 2009, xiv). Nor is this supplied by another major work influenced by Rosen, *Memory Evolutive Systems: Hierarchy, Emergence, Cognition* by Ehresmann and J-P. Vanbremeersch (2007), although a closely allied researcher, George Kampis, has pointed out the ontological implications of similar ideas (Kampis 1991, ch.9). To fully appreciate and further advance Rosen's work in theoretical biology not only as the basis for integrating work in post-reductionist biology, as an effective challenge to the pre-eminence of physics, and for providing the ontology that Rosen believed is required for this and thereby to advance physics as well as biology, it is necessary to situate this work in a much longer time perspective. It is argued here that it is necessary to examine and appreciate the efforts to overcome Newtonian physics and their achievements from the end of the Eighteenth Century, particularly those of F.W.J. Schelling and those he influenced. What we see when we adopt this longer time perspective is that there is a relatively coherent tradition characterized by intense efforts to empirically investigate the reality of life in all its dimensions generating equally intense efforts to develop new mathematical approaches adequate to the reality of life. It is a tradition that not only has made great progress, but in doing so has revolutionized not only biology but mathematics and physics, and Rosen's work when it is understood in the context of this tradition both provides the perspective required to reintegrate it, and points to what kind of work is now required to further advance it.

2. Schelling' Challenge to Newtonian Physics and its Influence

The case for taking biology as the reference point for science and reforming physics on this basis was first made by Schelling. While for a long time the contribution of Schelling to subsequent science was dismissed (Lenoir, 1982), this view has since been discredited, in the case of biology through the work of Robert Richards, although it still persists (Richards, 2002; Gare, 2011, 67).[4] However, even when the importance of Schelling's work is appreciated, the revolutionary implications of privileging biology over Newtonian physics remain under-appreciated.

Schelling's point of departure was first and foremost the work of Kant, most importantly, Kant's work on biology in the *Critique of Judgment.*[5] The *Critique of Pure Reason* was important for providing a notion of knowledge through construction and for clarifying the concepts of Newtonian physics that had to be overcome in order to provide a stronger defence of Kant's work on biology. In this earlier work Kant had characterized mathematical knowledge as synthetic *a priori* rather than analytic or empirical, arguing that we only really know what we ourselves have made or constructed, and he revealed the deep assumptions underlying Newtonian science that allowed the world to be understood through the mathematics of his day. In doing so, he highlighted how the physics developed on the basis of these assumptions was inconsistent with ethics and the possibility of genuine aesthetic taste, but also with the appreciation of natural purposes; that is, with the reality of life. In the *Critique of Judgment* Kant characterized natural purpose and clarified the difference between living organisms and mechanisms. A 'natural purpose', as an organized being 'must relate to itself in such a way that it is both cause and effect of itself', Kant claimed (Kant 1987, §65, 251). There are two requirements for this. '*First,* the possibility of its parts (as concerns both their existence and their form) must depend on their relation to the whole. … A *second* requirement … is that the parts of the thing combine into the unity of a whole because they are reciprocally cause and effect of their form' (Kant 1987, §65, 252). Since Kant had argued that intuitive knowledge gained through construction is confined to geometry and arithmetic and that the forms of intuition and the categories of the understanding underpinning Newtonian physics are constitutive of all experience, he held that the notion of natural purpose could be taken only as a regulative principle for the study of living organisms, not a constitutive principle. It is always possible that in the future the appearance of purpose will be explained mechanistically, and only through mechanism, Kant averred, can we really gain insight into the nature of things (Kant, 1987, §78, 295).

Schelling rejected Kant's demarcation or 'negative instruction' of what could be known through construction and argued that the whole of nature could be comprehended through intellectual intuition as nature's self-construction, with the constructive activity of the human subject being a part of this self-construction (Schelling, 1978, §4, 13; 1802, 125-151). He also rejected Kant's claim that the forms of intuition and the categories of the understanding could be established through a transcendental deduction

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[4] Schelling is represented by Lenoir as a vitalist (Lenoir, 1989, 124), despite Schelling's opposition to the notion of life-force (Schelling, 1988, 37), and then Karl Ernst von Baer and other scientists who embraced Schelling's research program, including his dynamic evolutionism (Richards, 2002, 312), are represented as breaking away from Schelling's influence.Apart from this, Lenoir does show that through an emphasis of Darwin 'we have overlooked a significant, valid alternative approach to biological phenomena during the early nineteenth century (Lenoir, 1989, 3).

[5] Schelling was also strongly influenced by Fichte, Goethe and Spinoza, among others. On this, see Gare (2011).

as true for all time as the conditions for knowledge. Naturalizing the transcendental, he argued that it is necessary to construe nature so as to make intelligible both its comprehensibility, and the evolution within nature and development through history of human consciousness which could comprehend it (Gare, 2011, 43). There are not absolute foundations for knowledge, and no knowledge claim can be taken as final; instead, claims to knowledge are circular, with his natural philosophy justifying belief in the reality and capacity of consciousness to know the world, and his work on idealism, justified by this conception of consciousness, showing how consciousness develops to be able to comprehend the world and itself, thereby justifying this natural philosophy. Instead of accepting Kant's defence of the concepts of existing physics Schelling argued that it is necessary to construct more adequate concepts to comprehend the physical world so as to make intelligible the emergence of life and then human consciousness. To achieve this, he rejected the role accorded to self-organization by Kant (in the *Critique of Judgment*) as just a marginal feature of the universe acknowledged as a regulative principle necessary for the study of natural purposes. Schelling saw the whole of nature as a self-organizing process that has generated force, extension, apparently inert matter (in which stability is achieved through a balance of opposing forces), space and time and living organisms. Nature is the activity of opposing forces of attraction and repulsion generating one form after another. Inverting Kant's characterization of causation, Schelling argued that mechanical cause-effect relations are abstractions from the reciprocal causation of self-organizing processes (Schelling, 1978, 110ff.). Matter is itself a self-organizing process. While 'matter' emerges through a static balance of opposing forces, living organisms were characterized by Schelling as responding to changes in their environments to maintain their internal equilibrium by forming and reforming themselves (anticipating Claude Bernard, the notion of homeostasis, and the more recent work of Turner, 2007), a process in which they resist the dynamics of the rest of nature and impose their own organization, constituting their environments as their worlds and reacting to these accordingly (anticipating Jacob von Uexküll's central idea). Animal and human consciousness evolved through this process (Schelling, 2004, 193ff.; Gare, 2011). For Schelling, 'Speculative Physics' is required to produce the concepts necessary to comprehend the self-constructive activity by which nature has evolved (Schelling, 2004, 193ff.). Developing the methodology of construction as the basis for all knowledge, of nature, humanity and all products of humanity, Schelling suggested the possibility of developing new forms of mathematics to achieve this comprehension.

There are a number of features of Schelling's conception of nature and of what constitutes knowledge of it that were important for the future of science. He argued that we are part of nature, so our comprehension of nature is simultaneously nature comprehending itself through us and our comprehension of ourselves as products of nature. It is essentially nature reflecting on itself and coming to know itself from the inside as a process of its and our self-formation. This requires of us that we distinguish ourselves as subjects from the rest of nature to achieve such knowledge, postulating what Schelling argued is an illusionary and misleading duality between ourselves as subjects and the world. However, Schelling argued, such knowledge presupposes living nature and only emerges from it, and we can know nature through reflection because we are part of, have emerged from, and are practically engaged within it. Initially, concepts are not developed through reflection but through action and then brought to full consciousness and refined through reflection. This includes mathematical concepts, although their development requires an intellectual reconstruction.

Re-examining the history of science it has become evident that many of the most important developments in the physical sciences since Schelling's time have been generated by physicists and mathematicians inspired directly or indirectly by Schelling's work, or where there is no influence, amount to a rediscovery of insights already contained in germinal form in the work of Schelling or those inspired by him. To begin with, there are the obvious influences (Esposito, 1977). Schelling's characterization of being as productive activity led scientists who had initially been influenced by Schelling but then turned their backs on him, most notably Hermann von Helmoltz, to develop the notion of conservation of 'force', later characterized as 'energy', a core notion of thermodynamics (Kuhn, 1977). His reformulation of dynamism according to which matter is generated by forces guided Oersted's discovery of electromagnetism which in turn influenced the development of field theory by Michael Faraday, whose ideas Schelling enthusiastically embraced (Williams, 1980, 48ff.).[6] Schelling was centrally engaged with the birth of modern chemistry as a science, which had been dismissed by Kant as lacking the systematic unity required for this status, and Schelling's explanation of diverse chemicals being the products of opposing forces foreshadowed the development of the concept of valence (Schelling, 1988, 221). Schelling's notion of self-organizing entities eventually led to the development of systems theory (Heuser-Kessler, 1986). While hierarchy theory (particularly as developed by Howard Pattee and those he influenced, according to which new levels of emergence involve new levels of constraint) was not directly inspired by Schelling (although there may have been an indirect influence through the work of Michael Polanyi), Schelling's notion of emergence through limiting of activity clearly anticipates this idea (1985, 144; 1993, ch.2). Closely similar is the recent insight by Kauffman that an evolutionary niche should be seen as an 'enabling constraint' (2009). And Schelling's evolutionary cosmology and his arguments for the evolution of terrestrial life, developed before Lamarck, influenced the development of later evolutionary theories (Richards, 2002). However, it is the less obvious influences, particularly associated with the quest to characterize knowledge in mathematics and of nature as an intellectual intuition of the process of construction, showing how new levels in nature emerge through evolution, that is more significant (Heuser-Kessler, 1992). These influences are most clearly evident in his immediate followers, but their work and the Schellingian tradition of *Naturphilosophie* inspired some of the most important developments in mathematics and mathematical physics in the nineteenth century.

One of the most important figures in the development of Schelling's research program to develop a mathematics through which nature could be known as constructive activity was Christian Samuel Weiss (Heuser, 2011). Embracing Schelling's holistic understanding of nature from which matter emerges through a constructive process, in 1804 Weiss speculated on the ultimate beginning of the universe, the formation of crystals and the formation of life. Following Schelling, he suggested that matter originated with a '*creatio ex zero*' through which opposing quantities emerged and existed through their separation, but which if brought into contact would annihilate each other and become zero again. That is, he postulated the existence of the equivalent of anti-matter, with matter and anti-matter being generated by a symmetry breaking process. Extension, he argued, is generated by difference as an infinite manifold which has to be grasped as a continuous multiplicity. He developed on this basis a mathematical theory of crystal formation as a part of the self-formation of nature. Introducing the concept of axis, Weiss was able to describe the seven crystal forms. This was his main contribution to science. However, Weiss saw this account of the self-formation of crystals as a starting point for investigating the self-formation of living matter. He argued that living matter, being a combination of fluidity and solidity in which neither can be subordinated to the other, involves different principles, and for the extension of the notion of nature as self-forming, Weiss demanded not only a new theory of dynamics, but new mathematical concepts. These

[6] Initially, Faraday was the assistant of Humphry Davy who was also influenced by Schelling through Coleridge, and with Faraday, combined Schelling's concept of matter as the product of opposing forces with Roger Joseph Boscovich's concept of the atom defined by forces of attraction and repulsion.

concepts should grasp nature not merely as external quantity of movement (characteristic of Laplace's physics) but as qualitative change in internal organization. These are the ideas that inspired Justus Grassmann who knew Weiss personally, who in turn inspired his son, Hermann Grassmann, with the same project (Gare, 2011, 43).[7]

Justus Grassmann, following Weiss, attempted to develop a new mathematics, what he thought of as a 'fluid geometry', that is, a 'dynamist, morphogenetic mathematics' that would facilitate insight into the emergence and inner synthesis of patterns in nature (Heuser, 2011, 58). As Michael Otte argued, 'J. Grassman defines mathematics in the spirit of Schelling, not Kant, as pure constructivity, as construction which does not start from any content or empirical intuition, but solely considers things according to the principle of noticing their equality or difference' (Otte, 67). It was crucial that this mathematics not be limited to a theory of quantity and be independent of all relations of quantity so that it could go beyond the extrinsic, mechanical behavior of matter and recognize the intrinsic possibilities within nature for structuring and organizing. Hermann Grassmann's work, which he characterized as the 'theory of extension', continued this project. He presented this work as a survey of a general theory of forms, assuming, as he put it, 'only the general concepts of equality and difference, conjunction and separation' (Grassmann, 1995, 33). Extended magnitude was defined as the magnitude created by the generation of difference in which the elements separate and become fixed as separate. It was not a theory of space but provided a foundation for such a theory. As Grassmann characterized the aim of his 1844 edition of his extension theory in his 1862 edition, it 'extends and intellectualizes the sensual intuitions of geometry into general, logical concepts, and, with regard to abstract generality, is not simply one among other branches of mathematics, such as algebra, combination theory, and function theory, but rather far surpasses them in that all fundamental elements are unified under this branch, which thus as it were forms the keystone of the entire structure of mathematics' (Grassmann, 2000, xiii).

This is essentially how David Hestenes and other recent champions of Grassmann's mathematics have interpreted his achievement, seeing him at the same time as the inventor of linear and multilinear algebra and the precursor to vector algebra, exterior algebra and Clifford algebra (Fearnley-Sander, 1979, 809). Grassmann's exterior algebra has also been recognized as a tensor theory that contributed to the development of tensor calculus utilized by Einstein in his general theory of relativity. Clifford algebra illustrates the generality of Grassmann's algebra. It uses Grassmann's theory to interpret William Hamilton's quaternions (Clifford, 1878), producing an algebra which is less universal because it requires some specification of local structure, notably, what 'perpendicular' means in order to define rotations (Hestenes, 2011; 244; Penrose, 2004, 211). J. Willard Gibbs and Oliver Heaviside independently of each other developed vector calculus, as Gibbs acknowledged, rediscovering Grassmann's work (Gibbs, 1881, 1). Gibbs in 1901 also utilized Grassmann's pioneering notion of multidimensional space to develop the idea of *n*-dimensional phase space in which every degree of freedom or parameter of the system is represented as an axis of a multidimensional space and every possible state of a system can then be represented as a point. Phase space was used to formulate quantum mechanics and for studying stability, bifurcations (including 'catastrophes') and chaos in systems. Ideas originating in Grassmann's work were also rediscovered and advanced independently by Paul Dirac to lay the foundations for quantum electrodynamics and quantum field theory (Penrose, 2005, 208ff., 618ff.). Ernst Cassirer, who was strongly influenced by Grassmann, observed that Grassmann had made modern physics possible by showing that 'the real elements of mathematical calculus are not magnitudes but relations' (Cassirer, 1923, 99). As

[7] The Grassmanns were also influenced by Schleiermacher, but then Schleiermacher was also influenced by Schelling (Gare, 2011).

Martin Horn noted, 'Grassmann is not only the forefather of the usual vector and tensor algebra we apply when we solve present-day physics problems conceptually. Grassmann's ideas developed into the innumerable concepts we possess today to model our world mathematically' (Horn, 2011, 436). It embraces multilinear algebra, projective geometry, distance geometry, hypercomplex function theory, differential geometry, Lie groups and Lie algebras (Hestenes, 1996, 198).

While it is significant that Grassmann's extension theory has served as a foundation not only for mathematical work that Grassmann knew about, but for the mathematics of Hamilton, Bernhard Riemann, Gibbs and Dirac and more recent work in mathematics, this is less surprising when it is realized that these mathematicians were inspired, directly or indirectly, by the same tradition of thought. Hamilton (one of the few mathematicians of Grassmann's time to appreciate his work from the very beginning) embraced Kant's constructivist philosophy of mathematics and was strongly influenced by and corresponded with Coleridge, who in turn had largely appropriated Schelling's natural philosophy. Hamilton's mathematics was developed as part of an attempt to develop a speculative metaphysics that would go beyond Newtonian science as it had been developed by Newton's successors and, as he wrote to Herschel with respect to Faraday's work, would show 'light, heat, chemistry, electricity, crystallography (with galvanism, magnetism etc. … to be all branches of one science, as yet imperfectly understood' (Hankins, 1977, 190). He saw algebra as providing the means to comprehend time. These are the ideas that enabled James Clerk Maxwell to model and advance Faraday's field theory of electro-magnetism on the basis of which he was able to oppose reductionist materialism (Harman, 1998). Riemann was even more strongly influenced by Schelling's research program. In accordance with Schelling, Weiss and the Grassmanns, Riemann argued that science should not be content with the observation and calculation of the exterior aspects of nature, but go 'further back behind the surface of nature' (Heuser-Kessler, 1992, 409). Riemann was concerned to develop a science that would go 'beyond the foundations of astronomy and physics laid by Galilei and Newton that would be in accordance with continuum theory' (Heuser-Kessler, 1992 409f.) and would give a place to life and freedom. He wanted a general field theory, although he was concerned with how discontinuities arose within continuous fields. Examining shock waves, he concluded that structure-building processes are non-mechanical and non-deterministic, showing in accordance with modern bifurcation theory that they exhibit a non-differentiable quality at a critical point. To comprehend this, Riemann looked for a law of freedom, concluding that 'freedom is very well compatible with strict lawfulness of the course of nature' (Heuser-Kessler, 1992, 411). Reflecting on the origins of life, Riemann argued, like Schelling, for an organizing principle that would explain the emergence of the first organisms from the inorganic. Also like Schelling, Riemann saw this organizing principle operating in human thought. As there is a progressive development towards higher levels of life, there is a progressive, creative process of thinking leading to higher levels of thought, he proclaimed.

Interest in Hermann Grassmann has revived in recent years, with efforts being made by David Hestenes and others to use his universal geometric algebra and calculus to provide the unifying foundation for all mathematical physics, offering new approaches to quantum theory and general relativity (Hestenes, 2011). However, what needs to be emphasized is that Grassmann's work continued the tradition of Schelling, Weiss, and his father, Justus Grassmann the goal of which was to provide the means to grasp the self-formation of nature, including life (Heuser, 1996, Radu, 2000; Petsche, 2009; Otte, 2011), and renewed interest reflects the success in physics of this whole research program in its opposition to the Newtonian tradition of physics.

3. Theoretical Biology in the Twentieth Century

When the source of the most revolutionary ideas in physics that transformed physics in the Twentieth Century is understood, then the paradoxical state of modern biology becomes more comprehensible. There has been a steady advance of reductionism apparently triumphing with the development of the synthetic theory of evolution, molecular biology and information theory. Reductionism privileges physics as the ultimate science to which all other sciences should be reduced. Ultimately, biology should be reduced to physics. However, those physicists who have been interested in and attempted to contribute to biology including Niels Bohr, Max Delbrück, Erwin Schrödinger, Eugene Wigner, Wolfgang Pauli and Walter Elsasser have been overwhelmingly anti-reductionist (Gare, 2008, 59). This paradox was highlighted by the contribution of a theoretical physicist to a conference organized by the theoretical biologist, C.H. Waddington. David Bohm noted that 'just when physics is moving away from mechanism, biology and psychology are moving closer to it. If this trend continues it may well be that scientists will be regarding living and intelligent beings as mechanical, while they suppose that inanimate matter is too complex and subtle to fit into the limited categories of mechanism' (Bohm, 1969, 34). This paradox becomes even more significant when it is realized that the impetus for this anti-reductionism in physics, without which its greatest achievements over the last two hundred years would not have occurred, has been the quest to characterize the physical world in a way that is consistent with the emergence of life and the human mind which reductionists have been so resolutely concerned to explain away.

Given the history of modern physics it should not be surprising that the main proponent of mathematical biophysics, Nicolas Rashevsky, should have been so concerned to avoid reductionism and develop a mathematical approach to life that did it full justice, and that his foremost student, Robert Rosen, and those influenced by Rosen, including Rosen's foremost student, A.H. Louie, should have continued this quest. It also should be no surprise that in their effort to do this they have been prepared to explore and develop new forms of mathematics and engage in deep reflection about the relationship between mathematics and reality and the nature of science itself. Situating their work in this context it should be easier not only to evaluate their work but to consider what directions should be taken next, specifically, to consider whether and how to complete Rosen's project of supplying an ontology. Furthermore, this should highlight the significance of taking Rosen's claim that physics has always had to retreat in the face of advances in biology seriously. Just as the mathematics inspired by Schelling's speculations designed to account for the emergence of life opened up new approaches to physics which eventually revolutionized it, it can be expected that advances in mathematical biophysics will offer new perspectives on current physics and perhaps revolutionize it again. However, this could require further rethinking about what mathematics is and its relation to science. To appreciate what is at issue it is necessary to also look at the broader field of efforts inspired by physics to do justice to the reality of life.

To begin with, it needs to be asked why the project inspired by Schelling did not succeed in delivering a fully satisfactory account of life. When appreciated as a development of Schellingian thought in which nature is understood as essentially process (with force, matter, extension, and space and time seen as emergents), Grassmann's mathematics provides the foundations for an interpretation of modern physics consistent with the possibility of the emergence of life and consciousness (in contrast to the reductionist materialism of the Newtonians). However, by itself, it does not provide the means to achieve this comprehension.

A major problem that needed to be addressed is the assumption about the goal of scientific knowledge identified by Rosen, that it is to develop a largest model, consisting of a set of states, and a recursion rule entailing subsequent states from the present states such that every other state of it can be obtained by formal deduction. It is this assumption that appears to have influenced the nineteenth century neo-Kantian scientists Hermann von Helmholtz and his onetime student Heinrich Hertz, both of whom were influenced by the tradition of *Naturphilosophie* inspired by Schelling, but who then reacted against it. They were largely responsible for the subsequent negative image and ignorance of *Naturphilosophie* and Schelling's contribution to science, and also of Kant's ideas on biology presented in the *Critique of Judgment* and the achievements of those biologists influenced by Kant (Lenoir, 1986, chap.5).[8] Helmholtz and his students strove to provide mechanist explanations for everything they studied, promoting mechanistic reductionism in biology and psychology and opposing Faraday's and Maxwell's field theory of electro-magnetism (Lützen, 2005).

Nevertheless, in doing so, they provided ideas that were important for the advance of the post-mechanist tradition. Denying any place for a life-force, Helmholtz postulated the conservation of 'force', which he understood only as a property of matter acting at a distance (Lenoir, 1982, 218). This conservation principle was later characterized as the conservation of energy and incorporated into thermodynamics which was then used to oppose Newtonian physics. Hertz, in his effort to re-establish physics on mechanistic foundations and meet objections to it and to refute Maxwell's field theory through experiment, managed to discover radio waves and confirm Maxwell's theory (which he then claimed was nothing but his mathematical equations).[9] In his effort to defend Helmholtz's reductionist conception of scientific explanation Hertz also introduced the notion of non-holonomic constraints that later could be turned against reductionism. Despite their failure to uphold Newtonian science in physics and their inadvertent contribution to post-Newtonian physics, they did succeed in maintaining the Newtonian idea of what characterizes genuine science. And as Rosen pointed out, so long as this Newtonian assumption about the ideal of scientific explanation is maintained, only mechanistic accounts of nature will be respected as truly scientific.

Before examining and evaluating Rosen's answer to these problems it is important to look at how other theoretical biologists have dealt with them. Of particular significance were Alfred Lotka's efforts to rethink biology through thermodynamics and to treat it mathematically, the work of those associated with the theoretical biology movement led by Joseph Needham, C.H. Waddington, Dorothy Wrinch and J.H. Woodger and continued by Rene Thom, Brian Goodwin, Mae-Wan Ho and the dynamic structuralists, and the biosemioticians led by Jesper Hoffmeyer, Kalevi Kull, Marcello Barbieri and Claus Emmeche bolstered by the work of Howard Pattee.[10] Lotka was the first major theoretician in the twentieth century to attempt a systematic mathematical treatment of all aspects of life influenced by post-reductionist physical science, having embraced the notion of energy as the basis for understanding life, including consciousness (Lotka, 1925, 50). However, he was only minimally anti-reductionist, and apart from his work on chemical oscillations, his maximum entropy production principle and his influence on ecology,

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[8] Helmholtz's opposition to *Naturphilosophie* was due partly to the lack of rigor in many of the *Naturphilosophen* who, disregarding Schelling's own work, reintroduced the notion of life-force – *Lebenskraft*. Lenoir's book reveals the extent and richness of the work on biology that was subsequently eclipsed by mechanist, neo-Darwinian biology.

[9] What is not generally appreciated is that this was a real clash of doctrines in physics that was effectively won by those influenced by *Naturphilosophie,* a victory obscured by the rise of positivism and reductionist biology.

[10] This is not exhaustive. For instance, important contributions to mathematics were made by biologists influeneced by Engels' dialectics. Claude Bernard was not only an important experimental and theoretical biologist but also called for the application of mathematics to biology. The Indian theoretical physicist Satyendra Nath Bose also made contributions to mathematical biology. See Bischof, 2003.

his major work, *Elements of Mathematical Biology* published in 1925, was most important for the impetus it gave to others, including Rashevsky, to apply mathematics to biology.

4. Mathematico-Physico-Chemical Morphology

The members of the theoretical biology movement, who characterizing their work as mathematico-physico-chemical morphology, were inspired by the work of Alfred North Whitehead and D'Arcy Thompson (Waddington, 1977, 22; Abir-Am, 1987). Whitehead was strongly influenced by Maxwell's physics (on which he wrote his fellowship dissertation) and Hermann Grassmann's mathematics (Whitehead, 1898, vff.; Riche, 2011), characterizing mathematics as 'the study of pattern' and its transformations, that is, 'with certain forms of process issuing into forms which are components for further process' (Whitehead, 1974, 114; 1968, 92). His work was directed at overcoming scientific materialism and providing the metaphysical foundations for a post-mechanistic conception of the world that could give a place to purpose and sentience in nature (Whitehead, 1968, 148ff.; Code, 1985). Science, he argued, 'is becoming the study of organisms', with physics investigating one kind of organism, biology another (Whitehead, 1932, 129). Members of the theoretical biology movement took up Whitehead's challenge to develop biology on the basis of this metaphysics. In *Growth and Form,* first published in 1917, D'Arcy Thompson applied geometrical analysis to examine large tracts of morphology. He argued that forms of nature that exist are the resolution at one instant of time of many forces that are governed by rates of change, and changes of form are brought about by changes of forces, but his main concern was to reveal the homologies between apparently different forms (Thompson, 1966, 14). The members of the theoretical biology movement attempted to comprehend the emergence and development of such forms. Woodger allied himself with Ludwig von Bertalannfy who had taken up the quest to comprehend mathematically epigenesis, that is, the differentiation and generation of such forms in the development of organisms (Bertalanffy and Woodger, 1933). As Needham described Bertalannfy's approach, 'Bertalanffy realises that there are strange realms in mathematics, unknown to most biologists, out of which concepts essential for the understanding of living systems may come, and can envisage the utilization for biology of order-systems not even involving number and quantity' (Needham, 1936, 24). With this in mind, Bertalanffy and Woodger appropriated the notion of field (from the German biologists Hans Driesch and A. Gurwitsch) and developed the notion of 'morphogenetic field'.

The notion of fields was further developed by Needham and Waddington who understood them as 'wholes actively organizing themselves', maintaining themselves and generating forms (Needham, 1936, 102). Epigenesis then was conceived as the emergence of a sequence of progressively more specific fields (as for instance, with the differentiation of the field of the whole organism the field of the brain emerges, from which in turn fields of the eyes emerge) producing progressively more specific forms. While Needham was concerned to examine the role of chemicals in this process, Waddington focused on the role of genes. He analyzed the canalization of development along self-stabilizing paths of development (chreods) characterized by a tendency for development to return to such paths after being affected by perturbations (homeorhesis), unless the perturbations are too great, in which case there might be a switch to a different path. He portrayed the possible chreods in a developing organism through 'epigenetic landscapes', with the different paths for the development of different forms represented as valleys. A number of genes could play a role in influencing the shape of these valleys, while each gene could influence a number of valleys. In characterizing the role of genes, Waddington pointed out the inappropriateness of efforts to treat them as containing information since 'a world of information [as defined by Shannon and Weaver] is essentially static, in that a system cannot engender new information from within itself; the only type of spontaneous change possible is a loss of information' (Waddington, 1976, 247f.). Through his own conceptual framework Waddington integrated genetics, development and evolution, a synthesis that is now being revived (Gilbert, 1991 & 2000).

Waddington attempted to extend his ideas mathematically, although he did not think he had succeeded. He was one of the first people to appreciate Alan Turing's 1952 mathematical demonstration of how a differentiated form could emerge from an initial homogeneous state (Turing, 1952). In a letter written to Turing soon after the publication of his paper, Waddington commended his work, but pointed to its limitations in that in biology there is never a completely homogeneous starting point, and more importantly, it is necessary to account for the regulation of scale that takes place in the development of embryos and show why distinct kinds of tissue are developed, and not intermediate types between these, issues that Waddington took up in later work (Waddington, 1952; Roth, 2011, 263f.; Waddington, 1962, 125ff.). Waddington's efforts to develop his ideas mathematically were greatly extended by his student, Brian Goodwin, who characterized his own work at this early stage as 'epigenetic thermodynamics' (Waddington, 1962, 45ff.; Goodwin, 1963). Then René Thom, largely inspired by Waddington's ideas, developed what came to be called catastrophe theory (by Christopher Zeeman), although Thom was as much concerned with structural stability as with change.

Through dynamical systems defined by vector fields, catastrophe theory models structural stability, with special attention given to abrupt changes of state caused by small continuous changes through a 'tipping point'. This is an abstract theory of morphogenesis independent of the substrate and the nature of the forces that create them. It is a qualitative mathematics in the sense that it meant to provide insight into the nature of reality rather than make exact predictions. As David Aubin noted in his study of Thom, of the tendencies Hilbert recognized in mathematicians, Thom chose to aim at '*intuitive understanding*, [fostering] a more immediate grasp of the objects one studies, a live *rapport* with them, so to speak', in contrast to those mathematicians who aim at greater abstraction, 'seeking to crystallize the logical relation inherent in the maze of material that is being studied, and to correlate the material in a systematic and orderly manner' (Aubin, 2004, 99). This qualitative mathematics, Thom claimed, is what is needed to characterize biological and other phenomena that have hitherto resisted mathematical treatment (Thom, 1975, xxiii). Of Thom's work, Waddington wrote in the foreword to the French edition of *Structural Stability and Morphogenesis*, 'as long ago as 1940, in my book *Organizers and Genes,* I urged the need to develop a topology of biology. In the intervening years, as not even an amateur mathematician, I have been quite unable to follow my own prescription. I am all the more grateful, therefore, to René Thom, who has now entered the field with such strong and extended effort' (Thom, 1975, xxi). These ideas are now seen as a branch of bifurcation theory and have proved fruitful in a whole range of disciplines, while the concepts developed by Thom, in particular, the notion of 'attractor' and 'basin' of an attractor have been central to the development of chaos theory and complexity theory (Aubin, 2004; Tsatsanis, 2012, 225).

While Thom later distanced himself from Waddington's work (Thom, 1989, 6), Goodwin continued to develop and apply forms of mathematics incorporating Thom's insights to the study of epigenesis. While he later embraced and contributed to advances in complexity theory as this was developed at the Santa Fe Institute (Solé and Goodwin, 2000), Goodwin's most original work was associated with the mathematical analysis of temporal organization and control systems in cells, analyzing the role of entrainment in biological organization and showing mathematically how coupled processes characterized by greatly different rates of oscillation interact to control biochemical processes (Goodwin, 1963), and later, with the mathematical modeling of biological fields controlling morphogenesis, providing positional information through phase differences between coupled cellular oscillators (Goodwin and Cohen, 1969; Goodwin, 1976). Avoiding both atomistic reduction and holistic description, Goodwin's work showed that 'the spatial organization of the whole derives from principles relating to the global field behavior together with constraints coming from the properties of the entities which are generated as parts' (Goodwin, 1987, 195). Goodwin and his colleagues then interpreted this work through the theoretical work of the structuralists, subsequently, characterizing their work as 'dynamical structuralism' (Goodwin, Sibatani and Webster, 1989). As Goodwin argued, referring to the work of Claude Levi-Strauss and Jean Piaget, 'A field … is an example of a *structure* in that it belongs to an invariant set (the harmonic functions) defined by internal relations (those defining the field equation over a domain), each member of which is a transformation of the other (by a change of boundary values)' (Goodwin, 1987, 197). While there were some variations in how this theoretical position was developed, a feature of it was that it combined what previously had been regarded as antithetical positions: structuralism and functionalism (Ho, 1989 & 2008). The dynamic structuralists recognized and interpreted their work on morphogenesis as a development of a tradition going back to Schelling's mentor, Wolfgang Goethe, and embraced Cassirer's argument that mathematics and science must now focus on relations (Webster and Goodwin, 1996).

Waddington and Goodwin also embraced the work of Ilya Prigogine on dissipative structures or self-organizing patterns generated through fluctuations or oscillations in thermodynamically far from equilibrium situations. While influenced by Théophile De Donder and von Bertalanffy's notion of open systems, Prigogine had been inspired by Henri Bergson (a philosopher indirectly influenced by Schelling through Ravaisson and Boutroux), particularly by Bergson's claim in *Creative Evolution* that 'The more deeply we study the nature of time, the better we understand that duration means invention, creation of forms, continuous elaboration of the absolutely new' (Bergson, 1983, 11). Prigogine was thus led to study irreversible processes associated with non-equilibrium thermodynamics, and always saw living beings as exemplifying these processes (Prigogine, 1977). Later, he came under the influence of Whitehead. The first examples of dissipative structures studied by him and his colleagues were hydrodynamic and chemical, explaining the Belousov-Zhabotinsky and other reactions. Their work involved developing the mathematics required to model the spontaneous formation of order in homogeneous chemical systems and defined the general conditions for self-organizing patterning. They then applied these ideas to biological processes, explaining the cellular differentiation and pattern formation in the slime mould and other organisms, and the dynamics of ecosystems (Prigogine, 1976; Nicolis and Prigogine, 1977 & 1989). Goodwin saw this as advancing Turing's ideas of pattern formation in excitable media (Goodwin, 1994, 97).

While the focus of the theoretical biology movement was on the development of embryos and the significance of this for understanding evolution, their work was not confined to these areas, and the ideas, including mathematical ideas, have been extended or linked not only to other areas of biology but to the physical sciences, psychology and the social sciences. Jean Piaget, whose study of cognitive development in animals and humans echoed Schelling's effort to characterize the development of cognition, aligned his own work with Waddington's developmentalism. He claimed that cognitive development (which includes the capacity of humans to understand and develop mathematics as a means to comprehend nature) has its own chreods (Piaget, 1971, 18ff.). Thom himself applied his ideas to study language and semiotics (Thom, 1983, 214ff.). Heinz von Foerster and Luis Rocha (von Foerster, 1977; Rocha, 1996; Rocha; 1998) have interpreted Piaget's constructivism through second-order cybernetics (building on the work of Gregory Bateson).

5. The Rise of Biosemiotics

A different branch of this tradition of theoretical biology influenced by Schelling is the work of the biosemioticians. The theoretical biology movement gave a place to signs, and influenced by the philosophy of Whitehead, strove to conceive life in a way that would make intelligible and give a place to teleology and the emergence of consciousness. However, the biosemioticians are led naturally to connect these phenomena through their focus on signs. The original members of this movement were inspired by the work of Jacob von Uexküll, C.S. Peirce and Gregory Bateson, among others, (Hoffmeyer, 2008, 3; Favereau, 2008; Barbieri, 2009; Favareau, 2010), and defended their research program by integrating it with the work of Howard Pattee. Von Uexküll argued that organisms can only be understood properly when seen in interaction with their environments which they define as their *Umwelt*, or 'surrounding world' (Kull, 2001). That is, they act on the basis of a model of themselves situated within their environments. This was a generalization of Kant's characterization of humans as actively constituting their worlds through imagination, forms of intuition and the categories of the understanding, but the notion that every organism has a world, as opposed to dead matter which does not, had already been suggested by Schelling, as noted above (Schelling, 2004, 112n‡; Gare, 2011, 55). Peirce straightforwardly described himself as 'a Schellingian of some stripe' and openly acknowledged that he was strongly influenced by Schelling's early work on the philosophy of nature (Gare, 2011, 64). Gregory Bateson was the founder of second order cybernetics (named as such by von Foerster) which took up again the problem raised by Schelling that we are part of the world we are trying to understand and cannot gain a perspective from outside this world. It investigates the construction of models of cybernetic systems, recognizing the importance of self-organization, that the investigators are part of the system they are investigating and consequently the inescapability of self-referentiality and the problem of the division between subject and object.

Peirce's target was mechanistic science, the belief that 'the laws of mechanics determine everything that happens according to immutable attractions and repulsion' and the 'instantaneous state of things from which every other state of things is calculable consists in the positions and velocities of all the particles at any instant' (Peirce, 1992, 300). While contributing to the development of mathematics and physics and affirming Kant's dictum that there is as much real science in a discipline as there is mathematics in it, Peirce questioned how far mathematics, at least as currently understood, could take science in comprehending the world. As he observed: 'It would seem as if there were an increase in variety [in the universe], would it not? And yet mechanical law, which the scientific infallibilist tells us is the only agency of nature, mechanical law can never produce diversification. That is a mathematical truth − a proposition of analytic mechanics; and anybody can see without any algebraical apparatus that mechanical law out of like antecedents can only produce like consequents. It is the very idea of law' (Peirce, 1955, 357). Nevertheless, it was through his reflections on mathematics that Peirce concluded that there are three basic categories, the categories of firstness, secondness and thirdness, applicable to anything that can be thought of. To reconcile science with the emergence of variety, including humanity, Peirce conjectured that lawfulness in nature emerged from indeterminate chaos which, through a tendency to take on habits, produced a difference which could be identified (a firstness), followed by something else, which introduced opposition into nature, which is a secondness. These opposing differentiated identities could then be connected, which is a thirdness. On this basis, Peirce defended an evolutionary cosmology in which a place could be given to final causation, and privileged 'semiosis', the production and interpretation of signs, over deterministic laws. His most general definition of a sign, again involving firstness, secondness and thirdness, was that which 'mediates between an object and an interpretant; since it is both determined by the object *relatively to the interpretant,* and determines the interpretant *in reference to the object,* in such wise as to cause the interpretant to be determined by the object through the mediation of the "sign"' (Peirce, 1998, 410). While Peirce argued that semiosis is ubiquitous in nature, his work focused primarily on semiosis in humans, with his main interest being in logic, mathematics and science. Most biosemioticians interpreted Von Uexküll's notion of *Umwelt* through Peirce's semiotics and extended this concept from animals to plants and cells. Following Kalevi Kull, symbolic semiosis associated with thought and language is seen to presuppose 'animal semiosis', semiosis where the interpretant is action, which in turn presupposes 'vegetative semiosis', where the interpretant is growth, which in turn presupposes semiosis within and between cells within the organism, that is, 'endosemiosis' (Kull, 2000; Hoffmeyer, 2008). The fusion of biosemiotics with Bateson's second order cybernetics has produced the new field of cybersemiotics (Brier, 2008).

Since Peirce and von Uexküll were inspired by the same tradition of thought, integrating their ideas did not present any major difficulties. Plant germination and embryogenesis were characterized as sign operations in which the DNA containing a coded version of the parents is interpreted by the fertilized ovule or egg and converted into a three dimensional organism, the interpretant (Hoffmeyer, 1996, 19f.). While this whole process can be seen as one semiotic act, it can be analysed into a multiplicity of smaller semiotic acts. For instance, the fertilization of an ovum can be seen as itself a semiotic act in which the ovum fertilized by the sperm constructively interprets the paternal input, resulting in the zygote (Huber and Schmid-Tannwald, 2008). Such vegetative semiosis reflexively incorporates the past and present into the future, anticipating not only the features of the environment the offspring will encounter on the basis of what the parent successfully defined as its surrounding world and survived within, but variations and unpredictable contingencies in this environment. Some grasshoppers, for instance, in response to signs from their environment can grow into locusts rather than normal grasshoppers, preparing them to adapt to a different environment than their parents, and embryos are generally equipped with some capacity to adapt to environments never previously encountered.

Some of the complexity of vegetative semiosis is illustrated by research on plants. As Günther Witzany (who was inspired by Ludwig Wittgenstein and Jürgen Habermas rather than Peirce) observed:

> We now know plants as highly sensitive organisms which actively sense their environment on different levels within their plant body (intraorganismic) and interact with same, related, and nonrelated plants (interorganismic); with nonplant organisms such as fungi, bacteria, and animals (transorganismic); and—additionally—with abiotic influences from the environment such as nutrient and water availability, light, gravity, wind, and temperature. … Plants assess their surroundings, estimate how much energy they need for particular goals, and then realize the optimum variant. Plants constantly take measures to control certain environmental resources. … Intraorganismic communication involves sign-mediated interactions in cells (intracellular) and between cells (intercellular). Intercellular communication processes are crucial in coordinating growth and development, shape, and dynamics. Such communication must function on both the local level as well as between widely separated plant parts. This allows plants to react in a differentiated manner to its current developmental status and physiological influences (Witzany, 2012, 1f.).

Such vegetative semiosis, which produces and maintains functioning structures, is shared by animals and humans and is the condition for their forms of semiosis.

To begin to account for such complexity, rapid development, anticipation and responses to new situations, it is necessary to recognize that development takes place at multiple semi-autonomous levels simultaneously, with levels transacting with each other. It is necessary to recognize that such development is controlled on the basis of memory and anticipation, and to conceptualize what this control involves and how it could emerge, and then show how such control relates to the laws of physics. Such control requires monitoring by the organism of itself and its environment, and this involves the interpretation of signs. Consequently, it is necessary to account for the possibility of the emergence of sign interpretations or symbols. And then it is necessary to account for how such control utilizing signs relating the past to the future can causally influences chemical processes.

René Thom offered a mathematical treatment of signs and their origins, defending Peirce's trichotomy between signs of Icon, Index and Symbol (Thom, 1983, 261ff.). However it was the work of Howard Pattee that was embraced by the biosemioticians. A theoretical physicist, Pattee has for over forty years attempted to explain these possibilities, and in doing so, has provided strong support for the biosemioticians (Pattee, 1968; Favareau, 2010). Doing so has involved facing up to the conceptual problems in modern physical science. The idea of nature governed by physical laws and the idea of symbols and semiotic controls are incommensurable. Laws are global and inexorable, while controls are local and conditional, and imply that events could be otherwise than they are. Semiotic controls require measurement, memory and selection which can be described statistically and are irreversible. They are not functionally describable by mathematically described physical laws based on energy, time and rates of change. However, they are structurally describable in the language of physics in terms of 'non-integrable' or 'non-holonomic' rather than 'holonomic' constraints (to use terms coined by Heinrich Hertz). That is, they are local rather than global constraints. Non-holonomic constraints facilitate hierarchical ordering different from the structural hierarchy of a crystal, which is characterized by a permanent loss of degrees of freedom, and from liquids and gases which have too few constraints. Non-holonomic constraints give a place to 'function', and as Pattee argued, a function is 'a process in time, and for living systems the appearance of time-dependent functions is the essential characteristic of hierarchical organization' (Pattee, 1970, 127). With this function the constraints must be variable and imposed on only select degrees of freedom of the constituent processes or entities.

Recognizing that there are degrees of freedom to be differentially constrained involves rejecting a central assumption of classical physics. It is always necessary to distinguish the observer from the observed, but the observer cannot be left out of account nor included in what is observed. This distinction is required by the assumptions of physics. Even Newton recognized a principled distinction between laws and initial conditions, and in general, the study of any system involves recognizing these initial conditions along with local control constraints of the measuring device, even if this is only a clock. These are the boundary conditions of what is studied in any experiment. While originally science was biased towards accepting the mathematically describable physical laws as ontologically basic and the problem of measurement derivative, as the significance of measurement came to be recognized in thermodynamics, relativity theory and quantum theory, the status of these opposing conceptualizations has been gradually reversed. To make such measurement intelligible in physical terms, von Neumann suggested that statistical concepts should be recognized as truly original and probability logics more fundamental than, and irreducible to, strict logics, with models of physical laws and semiotic controls being complementary. That is, it is necessary to uphold an ontology and cosmology of the kind Peirce proposed.

In the case of living organisms, this distinction between dynamics and the boundary conditions associated with measurement is involved in their very existence. Constructing a model of a self-replicating system, von Neumann showed that such a system must have not only material components but a symbolic description of itself as part of it, independently of any observer (von Neumann, 1966). For there to be reproduction, there must be measurements taking place in the system quite apart from any scientific investigation of these self-replicating systems. For the individual system to be a physical implementation, such self-replication requires that all the components that describe, translate and construct, be themselves described, translated and constructed within the 'self' that is being replicated. As Pattee argued, developing von Neumann's work, there must be 'semiotic closure' (Pattee, 2008, 127).

Following Michael Polanyi, Pattee argued that controls associated with such self-replication in organisms form a subsumption hierarchy in which there is emergence through the introduction of further informational constraints, echoing and augmenting Schelling's insight that emergence of new levels of organization and freedom come about through limiting activity. (Polanyi also argued that to properly understand these holistic aspects of systems it is necessary to 'indwell' in them, again echoing Schelling's view that nature should be grasped from the inside (Polanyi, 1958, 195f.)). There can be many levels of such hierarchical organization through such constraining of constituent processes (Pattee, 1973) involving a form of downward causation. The constraint of selection of variant offspring is one, but only one, of these constraints. These hierarchically ordered constraints are facilitative, opening up new possibilities by closing off other possibilities, with the most important facilitative constraints being associated with codes. Just as the codes of languages make possible an enormous range of utterances, so the natural codes make possible an enormous range of biological structures, processes and activities. Developing these ideas, Pattee's work was ideally suited to providing a rigorous defence of biosemiotics.

Marcello Barbieri, the biosemiotician whose work has focused most on codes, argues that natural codes have three features: they bring into correspondence two independent 'worlds', there is a system of molecular adaptors, and there is a set of rules that guarantee biological specificity (Barbieri, 2008a, 189). The first of these codes, associated with the origin of life, Barbieri claimed (to some extent in opposition to Hoffmeyer) are the 'ribosoids' consisting of RNA and proteins which synthesize proteins (one world) from genes (another world) according to specific rules. Such codes are an essential component of life, and, he argues, precede interpretation (Barbieri, 2008b). This is only one code, however, and Barbieri has described a range of codes, including the splicing codes of eukaryotes, the adhesion codes of multicellulars, the pattern codes of animals and the linguistic codes of humans (Barbieri, 2003, 233). Hoffmeyer and Emmeche argued (following Gregory Bateson and Anthony Wilden), that codes can be digital or analogue (Hoffmeyer and Emmeche, 1991). Digital codes are based on discrete sign tokens (which require stable structures that can be maintained through the vicissitudes of environmental changes) with an arbitrary relation between the sign and the signified. Such codes free messages from the constraints of natural laws, allowing 'impossible' interpretants, such as organisms that are incapable of surviving, to be produced. They are relatively free from the flux of becoming, and so are ideal for memory, and they facilitate abstraction and thereby meta-messages, a role played in organisms by regulatory genes (Hoffmeyer, 2008a, 87f.). Each of these characteristics facilitates greater plasticity and creativity, but at the expense of dissociation from immediately recognizable processes on which digital coding is ultimately dependent. Analogue coding, by contrast, is indexical or iconic, based on some kind of similarity within the spatio-temporal continuity, or in internal relations such as between cause and effect, or in the relation between part and whole (Hoffmeyer, 2008, 89). Digital and analogue codes and the processes they control can and do interact with each other, and this interaction generates much of the enormous complexity associated with organisms, and as Hoffmeyer argues, makes evolution possible.

However, while codes can account for a great deal of the complexity of life, there are other ways in which complexity can be generated, and these interact with the processes generated by codes (Kauffman, 1993 & 2000; Cohen, 2003). An effort to take into account all this complexity, combining thermodynamics, Peircian semiotics and Pattee's work on symbols, facilitative constraints and hierarchical order, has been undertaken by Stanley Salthe (1993), reconciling biosemiotics and hierarchy theory.

6. Rosen's Relational Biology

Rosen was at one time a colleague of Pattee and engaged with similar problems. Like Pattee, he also was strongly influenced by von Neumann and centrally concerned with the problem of measurement; he also accepted von Neumann's argument that a self-replicating system must include a representation of itself. Like Pattee, he argued that emergence, including the emergence of life, involves non-holonomic constraints which 'limit the number and kinds of behavior which the system can exhibit' (Rosen, 1988, 23). Non-holonomic constraints, he pointed out, are not global but local, being a function of other phase variables. As these constraints are increased, velocity comes to depend entirely on configuration and can be specified as a vector field in configuration space. Such systems 'cannot be treated by classical mechanical ideas at all' (Rosen, 1988, 25). It is not at all clear that Rosen abandoned his interest in emergence through non-holonomic constraints (as Pattee apparently believed − Pattee, 2007). But in his later work, Rosen became more interested in mathematically modeling the distinctive features of life itself - most importantly, anticipation, independently of its material substrate - and more radically questioning received ideas about modeling systems. In following this path Rosen was advancing von Bertalannfy's general system theory and the relational biology of Rashevsky while utilizing Category Theory as developed by Saunders Mac Lane.

Rashevsky described the goal of mathematical biophysics in 1936 at a meeting with Niels Bohr and others in Copenhagen. It was to develop 'mathematical biology as a rational theoretical science, according to patterns suggested by theoretical physics' (Abraham, 2004, 360). He invented one of the first models of the neuron and originated the idea of neural networks based on the idea of continuous modeling. Walter Pitts, who with Warren McCulloch created the idea of a discrete, logic based neural net, the foundation for digital computers, was one of Rashevsky's students. Dissatisfied with his piecemeal approach that missed the nature of life as such, Rashevsky then redefined his research direction to look for general principles in biology. To begin with, he looked at the principle of Optimal Design, examining how 'for a set of prescribed biological functions the organism has the optimal possible design with respect to economy of material used, and energy expenditure, needed for the performance of a prescribed function' (Cull, 2007, 180), rejecting the idea that such design could be explained as nothing more than the effect of natural selection. Later, he attempted to formulate more general principles, offering a topological analysis focused on relations between functional components and the whole organism rather than on measurement.

Although he studied at Göttingen, the stronghold of Hilbert's formalism, Mac Lane rejected formalism. In accordance with Schelling's understanding of concepts, he argued that mathematical concepts originate in practices and only then are refined and elaborated as mathematical concepts (Mac Lane, 1981; 1990). Mathematics cannot be understood as simply the manipulation of rigorously defined terms according to specified rules. Henri Poincaré had shown how to create algebraic models of geometrical objects, and then group theoretic images of topological spaces, then how to deduce properties of the latter from the former. These ideas were further developed by Emmy Noether by applying group theory to topology. Her insights provided the basis for B.L. van der Waerden (in 1930) to reconceive algebra as the elucidation of structures of which groups, ideals, rings, fields etc. are individual realizations. On this basis, Oystein Ore in 1935 attempted to develop a general foundation for abstract algebra through the concept of 'lattice', which he designated 'structure'. This new image of algebra as the study of structures was embraced by the Bourbaki group and extended from algebra to the whole of mathematics, although as Leo Corry has shown, their own concept of structure contributed little to the development of this new conception of mathematics (Corry, 2004). It was the development of Category Theory by Samuel Eilenberg and Mac Lane in 1945, Corry argued, which provided the formal tools and perspective required to elucidate the non-formal notion of mathematical structure, in doing so, developing a general theory of modeling relations within mathematics. As Rosen described this:

> Category Theory comprises … the general theory of formal modelling, the comparison of different modes of inferential or entailment structures. Moreover, it is a stratified or hierarchical structure without limit. The lowest level, which is familiarly understood by Category Theory, is … a comparison of different kinds of entailment in different formalisms. The next level is, roughly, the comparison of comparisons. The next level is the comparison of these, and so on (Rosen 1991, 54).

Effectively, this offered a formal image of the modeling process itself that could then be used to investigate the relations between different inferential structures within mathematics (Rosen, 1990. 196f.) This was then utilized by Rosen to analyse modeling generally, expressing in a purely mathematical realm the pattern of relations between one model and another and between models and 'objects', including the relationship between mathematical models and what is modeled in the world (Rosen, 1993).

Through his relational biology Rashevsky, like Pattee, was reintroducing the notion of 'function' which had all but been excluded from mainstream biology and from science generally, except when it was taken as shorthand for why some feature of a species of organism had been preserved in the struggle for survival. Rosen utilized Category Theory to examine the assumptions of Aristotelian and Newtonian science and the relationship between Newton's assumptions and the mathematics deployed by him and his successors, revealing thereby how science had locked itself into a path that denied the objective reality of function, and more fundamentally, of final causes, and thereby excluded the fundamental question 'What is Life?' He showed how reductionists avoid this question by constructing a small surrogate universe of various fractionated components of organisms that can be explained by methods that have sometimes worked in other areas of science, and then taking these isolated fractions as the surrogate for the whole living system. They then identify science with the methods used to investigate these fractions. The possibility of revealing this to be deficient is then blocked by redefining science - not through its content and the kinds of questions it must answer - but by specifying the method of investigation, which is then identified with what is 'objective'. This has led to the exclusion of final causes on the grounds that there is no objective scientific method for studying final causes, confusing the meaning of objectivity, a confusion illustrated by Jacques Monod's claim that: 'The cornerstone of the scientific method is the postulate that nature is objective. In other words, the *systematic* denial that "true" knowledge can be reached by interpreting phenomena in terms of final causes – that is to say, of "purpose"' (Monod, 1974, 30). Unraveling this confusion, Rosen showed the real issue and the real problem to be how to develop a mathematical structure in which the logical entailments within the mathematics models adequately reflect the causal entailments in what is investigated. In biology, what is being investigated are living beings. Rather than invoke an inadequate surrogate universe, it is necessary to appreciate the full reality of life itself characterized by final causes and functionality of components (Rosen 1991 108ff.). Functional components cannot be fractionated and treated independently of the organism since they are aspects of and definable only through the whole organism.

Recognizing a place for final causes, Rosen set out to model anticipatory systems, systems which do not simply respond to their environments but anticipate and respond to what will happen in the future (Rosen, 2012). That physics at present has no place for the influence of future conditions and final causes indicates, Rosen argued, that it is too specific and conceptually limited, just as nineteenth century physics was too specific and conceptually limited to account for atomic spectra, radioactivity and chemical bonding. Just as to explain these required the conceptual revolutions of relativity theory and quantum theory, so a new conceptual revolution is required. Rosen questioned the primacy given to closed systems in science, arguing that open systems are generic, and a closed system is an extremely degenerate case of an open system (Rosen, 1987, 316). Along with this, he also questioned the notion of 'state' in science and reality, suggesting that it is a fiction. The conceptual revolution required to account for life will also require a new mathematics. The mathematics of Heaviside and Dirac gave a place to discontinuous signals (the δ-function), which were initially discounted or denigrated (by von Neumann among others) as not genuine mathematics. Nevertheless, they eventually had to be accepted and the old mathematics relegated to the status of a special case. Similarly, new mathematics will have to be developed that will relegate the old mathematics to the status of a special case (Rosen, 1991, 28ff.) This is what Rosen set out to do.

Modeling anticipatory systems involves modeling systems that produce their own components (in accordance with how Kant and Schelling understood living organisms). To do this, they require models of themselves (as von Neumann argued). Such systems, Rosen showed, can be represented through synthetic models in which functional components are the direct product of the system. In these models the components are context dependent, and cannot be reduced to fractional parts conceivable independently of the models. Such systems are complex, but not as mainstream complexity theory understands complexity. This theory, Rosen claimed, had not freed itself from Newtonian assumptions and dealt only with the complicated. Genuine complexity requires multiple formal descriptions which are not derivable from each other, to capture all their properties. The example Rosen produced to illustrate this was his metabolism, repair, reproduction models (the M-R systems). These models consist of three algebraic maps, one of which represents the efficient cause of metabolism in a cell, another, the efficient cause of repair (that repairs damage to the metabolic processes), and the third represents replication which repairs damage to the repair process (Rosen, 1991, 248ff.). Each of these maps has one of the other two as a member of its co-domain, and is itself a member of the co-domain of the remaining map. The maps thus form a loop of mutual containment. As Rosen put it: '*a material system is an organism if, and only if, it is closed to efficient causation*. That is, if *f* is any component of such a system, the question "why *f*" has an answer within the system, which corresponds to the category of efficient cause of *f*' (Rosen, 1991, 244). On the basis of such models it is possible to appreciate the ability of complex systems to incorporate models of themselves in their environments into their behaviour, anticipating future events and correcting their behaviour as new information sheds light on the anticipatory process (Rosen, 2000, 199).

Such models, being reflexive, contain self-referencing definitions or 'impredicativities', the 'vicious circles' that Bertrand Russell claimed were always associated with self-referential loops. These, Russell argued, had to be avoided through his 'theory of types' which prohibited self-reference (terms being defined appearing in the definition). Rosen claims that organisms, having models of themselves, are full of impredicativities. The effort to exclude these was part of the effort to achieve certainty in mathematics by reducing the semantics of mathematical language to syntax; that is, the rules of how we are permitted to manipulate terms from one proposition to another, while ruling out any reference to what terms denote (such as the geometrical object 'triangle', and beyond this object, to triangular objects in the perceived world). If this were possible, then mathematics could be identified with what is computable on a digital computer. 'Objectivity' in mathematics would then be equated with computations that can be carried out by a properly programmed machine. It would be a matter of software and hardware. Such a machine, Rosen pointed out, 'is, in material terms, entirely a classical device, both in its hardware and in its software; all it could see of a non-classical, quantum realm is noise' (Rosen, 1996, 211). However, as he also pointed out, this program of reducing semantics to syntax was shown by Kurt Gödel to be impossible. Gödel showed further that what is modeled by a formal system in which all entailment is syntactical entailment is richer and more complex than its model. Just as arithmetic cannot be fully encompassed by the model of it formulated through set theory and logic, the richness of natural systems (selected portions of the external world) cannot be encompassed by arithmetic, or any other formal model of them. Selecting a natural system and measurement are, and should be recognized as, abstractions. Restricting models to classical computable models, as noted in the introduction to this paper, would entrench the identification of objectivity with the elimination of final causes and the mechanistic view of nature. But, as Rosen pointed out, systems governed by syntax alone are small, inferentially weak and are not generic of mathematical systems as a whole, which are full of impredicativities. These provide the entailments to model living organisms with semantic elements that depend entirely on the context created by the circle of self reference associated with the reflexivity of anticipatory systems (Rosen, 2000, 135f.). Such models involve necessary ambiguities and cannot be simulated on a computer, and this is what makes them indispensible for understanding biological and cognitive functions (Louie & Kercel, 2007).

7. Completing the Project of Overcoming the Newtonian Paradigm

By offering a history of post-reductionist mathematical biology and physics from the perspective of a tradition of science inspired by Schelling under the influence of Kant and Goethe and characterizing its development, I hope to have shown that real progress has been made in this tradition, even though it is seldom recognized as a tradition by those who have advanced it. It is a tradition that has assumed and then developed Kant's insights on knowledge, mathematics and biology and defended these more strongly and taken them further than did Kant himself, or most of his neo-Kantian champions. Many neo-Kantians, inspired by von Helmholtz's 'Back-to-Kant' movement, which was really a movement to oppose the influence of *Naturphilosophie,* adhered to Kant's claim that 'without mechanism we cannot gain insight into the nature of things' (1987, §77). Like von Helmholtz, they held that to be truly scientific, biology must seek reductionist, mechanistic explanations and allow no role to purpose (Lenoir, 1982, 197ff.). Kant's concept of 'natural purpose' was accepted only for its heuristic value. Although Kant himself was opposed to evolutionary theories, this approach could be assimilated easily to and lend support for Darwinian evolutionary theory. It is this attitude that led von Bertalanffy to complain that 'Kant who, in his epoch, appeared to be the great destroyer of all "dogmatism," to us appears as the paradigm of unwarranted absolutism and dogmatism' (von Bertalanffy, 1968, 227). However, there were exceptions, and these are now becoming more common.[11] The neo-Kantian Ernst Cassirer (admired by von Bertalanffy) advanced Kant's work and in doing so, had a significant influence on the dynamic structuralists (Webster and Goodwin, 1997, 104ff.). Cassirer did so by embracing ideas originally developed by Schelling and those he inspired. He was strongly influenced by Hermann Grassmann's

[11] See for example the work of Gertrudis van de Vijver.

mathematics and philosophy, using this work to argue that from then on science should focus on relations and functions. He then defended Goethe's work on morphology and, like a number of other Kantian philosophers of science, gave a place to conceptual revolutions. These developments not only accorded with Schelling's philosophy but supported Schelling's argument for Speculative Physics. But Schelling was barely mentioned. While this is beginning to change with more recent neo-Kantian work in theoretical biology, this typifies the tendency to ignore or misrepresent Schelling and then to deny his influence while advancing his ideas.

Achieving proper recognition for Schelling by itself is relatively unimportant, however. What matters is that through ignoring or misrepresenting the range of contributions to mathematics, physics, chemistry, biology and cognitive development by Schelling and those directly or indirectly influenced by him, and also the contributions of those who developed similar ideas independently, there has been a fragmentation of and weakening of the potential of the research of those striving to overcome the Newtonian paradigm. This brief history is designed to identify and thereby recover the history of what is really a tradition that has inherited and then developed assumptions and goals and made major advances over generations, while not being recognized as a tradition. By identifying post-reductionist science as a tradition the aim is to reunify it, to orient those committed to overcoming the Newtonian paradigm in biology to advance this project, and to provide support for all those engaged in this project. In particular, this history is designed to suggest how mathematical, theoretical and empirical work by the theoretical biology movement focusing on epigenesis aligned with work on cognitive development, work by the biosemioticians on semiotics and work by relational biologists on anticipatory systems might better be brought to bear on each other and be situated in relation to mathematics and other sciences. Of course this is not meant to exclude recognition of other developments in post-reductionist science not even indirectly influenced by Schelling. Some examples of these are described by Letelier et.al. (2011). The most important instance of such work has been the development of Category Theory building on the work of Henri Poincaré who, as a French neo-Kantian, was not in any way influenced by Grassmann's mathematics. And individual researchers by virtue of their own observations or insights that challenge mainstream assumptions, and then struggle to have their voices heard, should always be recognized as among the most important contributors to the advancement of science. What is presented is meant first of all to strengthen the claims of all researchers whose work brings into question prevailing reductionist assumptions, to show where resources can be found to further defend and develop their work, and then to offer some suggestions for further research. These should be taken as suggestions, not prescriptions.

What contribution does it make to recognize an anti-reductionist tradition in mathematical biology? Both the theoretical biology movement inspired by Whitehead and the biosemiotic movement inspired by von Uexküll and Peirce insisted on giving a place to teleology and function in nature and life. However, in both cases they did so by delimiting the domain of validity of mathematics while still according a place to mathematics. The significance of Rosen's work, building on the work of Rashevsky and Mac Lane, is that he has shown how final causes can be modeled mathematically. He has thus legitimated the role that other anti-reductionists accorded to teleology and function, greatly strengthening the claims they make for their insights made on this assumption. However, as noted, Rosen's work was unfinished, and it has not been finished by his disciple, Louie. There are questions about the relationship between his earlier work done in collaboration with Pattee and his later work. His later work was concerned with the nature of biological order independent of its material substrate, but despite Pattee's qualms, it would appear that there is no reason why anyone embracing the arguments of Rosen's later work would dismiss his work on hierarchical order, or assume that he did not accept that biomolecular structures and biogenetic processes are required to support and allow the emergence of functional ultra-complexity. With minor modifications, Rosen's work should provide a rigorous framework for defending, integrating and further advancing the work of both the theoretical biology movement and their allies and the biosemioticians.

To achieve this, it is necessary to complete Rosen's project of providing an ontology. That Rosen believed this necessary is not surprising if we appreciate his defence of Aristotle's approach to science and his condemnation of efforts to define science as a method. Just as he believed it is necessary to ask the question What is Life? it is necessary to ask the question What is Being? Such an ontology should provide the basis for assessing and integrating other work in science, including related work in biology, and orient science for new research. Rosen clearly had this in mind, and believed that the insights he had gained through the study of life could illuminate physics, the social sciences and politics as well as biology. By situating the tradition of mathematical biophysics in relation to and as part of the broader tradition of post-reductionist thought, which includes also the theoretical biology movement and the new tradition of biosemiotics, it should become clearer what this ontology would be and how it would facilitate the integration of work in mathematical biophysics, the theoretical biology movement and biosemiotics. From there it should be possible to get a clearer idea of the challenges facing this tradition and how these challenges might be met. It should also be possible to gain a clearer insight into the importance of this work for physics and the other physical sciences, and for society. However, it should also reveal where Rosen's work can be fruitfully revised and built upon.

Since this anti-reductionist tradition of mathematical biology originates in the work of Schelling, it is his conception of being that should be taken as the starting point for characterizing this new ontology. As Schelling argued, ontology has to give a place within nature to human consciousness of nature. We must recognize that we are part of the world that we are trying to know, with all the problems this poses for characterizing this knowledge. Central to Schelling's proposed ontology, making intelligible the emergence and evolution of life and consciousness, is that it is self-organizing activity (or 'productivity'), in which forces, matter, space and time, living organisms and consciousness, including our consciousness of nature and ourselves, are products generated by this self-organizing process through limiting activity, with the products of this process: matter, organisms and humans themselves, being self-organizing participants in this process. Self-organizing activity involves 'community of causation' or immanent causation in which relations are essential and central. These are the basic ideas which were then reworked by a tradition of natural philosophers and metaphysicians in the tradition that originated with Schelling, including Bergson, Peirce and Whitehead. As Kampis showed in his work on self-modifying systems, these are the ideas consistent with his own and Rosen's work (Kampis, 1991, 462ff.). While this is still a developing tradition with no final consensus on the characterization of physical existence, it is a tradition that has privileged temporality in the process of creative becoming and treated what previously had been assumed as basic to physical existence (such as space, measurable time, matter and lawful dynamics as understood in the Newtonian tradition of thought) as derivative products of this creative becoming that must be accounted for. In doing so it gives a place to indeterminacy and emergence, to multiple levels of becoming based on different process rates and temporal scale as well as spatial scale, and in one way or another, to anticipation and final causes. It was a version of this ontology that Rosen appears to have been developing, granting a central role to relations and to the complexity of temporality.

Rosen embraced Rössler's endophysics which sought not only to defend but reveal the implications of accepting that we are part of the world we are striving to know (Rosen, 1993). Like Schelling, Rosen appreciated the problematic status but necessity of the discriminations required to gain such knowledge; that is, to know the world of which we are part we have to differentiate ourselves from the world. 'Science is built on dualities' Rosen wrote, and 'the most fundamental dualism, which all others presuppose, is of course the one a discriminator makes between self and everything else' (Rosen, 1991, 40). He characterized 'everything else' as the self's ambiance. The second dualism is associated with the partition of this ambience between systems and their environments. Rosen interpreted the role of models on the basis of such discriminations, that is, between the model and the system modeled, introducing a third dualism.

A criticism that can be leveled at Rosen in this account of partitioning is that he has recognized only dualities, that is, the dualities between the self and its ambiance, between systems and their ambiance and then models and what the systems modeled. This is one place where Rosen's work could benefit from other advances in the post-reductionist tradition. Peirce in his efforts to develop and augment Schelling's ontology had already pointed out that most of the aporias of modern thought derive from such dualisms, and showed how these could be avoided by recognizing triadic relations (Gare, 2007, 5f.). Semiosis, for instance, involves not just a sign and its object, but a sign, its object and its interpretant. In the case of science, there is at least the proposition formulated by an investigating scientist (for instance a mathematical model), the object being investigated (the system being modeled) and the interpretant, the idea in the mind of another scientist listening to or reading the work of the first scientist. Similarly, in a sympathetic study of Rosen, Cottam, Ranson and Vounckx have rejected Rosen's binary separation of assemblies into mechanisms and organisms and called for a threefold segregation so that the organism can be seen as the complex interface between mechanism and ecosystem (2007).

Cottam, Ranson and Vounckx also argued that his relational biology needs to be modified to give a proper place to scalar hierarchies, arguing that they were not properly dealt with by Rosen. This criticism reinforces Pattee's criticism of Rosen's later work, suggesting that after writing *Anticipatory Systems* Rosen had abandoned the ideas on which they had worked together for a more mathematical and more 'idealist' approach, in contrast to his own physicalist and 'materialist' approach (Pattee, 2007). In fact Rosen did describe physical existence involving different levels of organization associated with constraints years after the publication of *Anticipatory Systems* and while he was working on *Life Itself* (Rosen, 1988). The difference between Rosen and Pattee was that Rosen broke more fundamentally with classical physics and the privileged place it accorded universal, inexorable, physical laws. That is, through his work on modeling and the problem of modeling Aristotle's four causes, Rosen moved closer to the tradition of Schellingian and Peircian ontology. As Louie pointed out, Rosen's defence of Aristotle's four causes involved developing a notion of immanent causation (Louie, 2008). It was Schellingian rather than Aristotelian, and from this perspective, Rosen saw apparently inexorable physical laws not as the reference point for all science as Pattee has continued to do, but as localized and in need of explanation. The problem is that he did not discuss hierarchies based on non-holonomic constraints and M-R systems at the same time. That he did not forget his work on hierarchy is evident in his appreciation of the complexity of time. His daughter Judith Rosen and John Jay Kineman pointed out that Robert Rosen saw time as a relational concept, and so as complex, involving multiple time-scales (Rosen and Kineman, 2005). Measurement of time must be utterly context-dependent, and this is also the case with the modeling of temporal processes by organisms when they anticipate the future, as when trees anticipate cold weather on the basis of changing length of days and shed their leaves before temperatures drop below freezing. Judith Rosen further conveyed the central place her father accorded temporality in her introduction to the new edition of *Anticipatory Systems* published in 2012: 'Living organisms have the equivalent of one "foot" in the past, the other in the future, and the whole system hovers, moment by moment, in the present – always on the move, through time. The truth is that the future represents as powerful a causal force on current behaviour as the past does, for all living things' (J. Rosen, 2012, xi). Nevertheless, by giving a place to scalar hierarchies, Cottam et.al. have provided the means to better integrate Rosen's concern with hierarchy and his work on anticipatory systems.

Stanley Salthe's work on hierarchy theory further clarifies this relationship. Salthe attempted to integrate hierarchy theory and Peircian semiotics along with other work, including Rosen's ideas, tracing out a general theory of development and evolution. 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 shorter and longer scales and faster and slower rate processes, modifying both the longer and the shorter scale processes (1985, 145; 1993, ch.2; 2012). Granting a place to scalar hierarchies also helps clarify the nature of 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' (1993, 270). The essential temporality and process nature of anticipation has been also clarified by Nadin (2012).

An idea of what the mathematical integration of Rosen's work on anticipatory systems and hierarchy theory would look like can be gained from Louie's further development of Rosen's ideas (Louie and Poli, 2011) and also from the work of Eherensmann and Vanbremeersh on memory evolutive systems, a mathematical theory deploying Category Theory and influenced by the work of Rashevsky and Rosen. This has been further developed by integrating other mathematical ideas, including Baas' work on hyperstructures, which explain emergence, and Simeonov's work on Wandering Logic Intelligence (Ehresmann and Vanbremeersch, 1987 & 2007; Baas, Eherensmann and Vanbremeersch, 2004; Eherensmann and Simeonov, 2012). The outcome is a rich mathematical framework that is able to relate memory and anticipation, levels and time scales, interaction and complexity, and emergence. Its authors have specifically related memory evolutive systems to Rosen's model of organisms, showing their consistency while at the same time identifying the condition for the emergence of objects and systems of increasing complexity during the course of evolution (Ehresmann and Vanbremeersch, 2006).

Interpreting Rosen's work as a development of the tradition that goes back to Schelling, integrating hierarchy theory with the notion of anticipatory systems both strengthens Rosen's work as a means to justify other anti-reductionist ideas in biology, while at the same time allowing Rosen's work to be augmented by these other traditions. His work can be used to defend the work of the biosemioticians, which in turn could be used to further augment Rosen's research program. Eliseo Fernández, for instance, has shown how the insights of Peirce and Rosen illuminate each other, clarifying the presupposition about temporality in Peirce's characterization of semiosis while at the same time further clarifying Rosen's notion of self-referential anticipatory systems and the place temporality has to play in these (Fernández, 2008; Fernández, 2010; Goudsmit, 2009). As she points out, the relations associated with self-reference and with semiosis are essentially durational, and as such, tend to be obscured by static diagrams. As she put it, 'A sign does not exist at any singular, particular instant, just as motion does not exist instantaneously. Like motion, semiosis is radically temporal, in the sense that its parts cannot coexist in the way that spatially individuated objects do' (Fernández, 2010, 154). It is by virtue of this that the interpretant, besides representing the object, is able to represent the very relation of representation which the sign has to that object. Ricardo Gudwin and João Queiroz have attempted to provide a mathematical model of Peircian semiosis that they call 'Mathematical Semiosis' using Rosen's ideas on anticipatory systems to achieve this (Gudwin and Queiroz, 2007).

However, this is hardly an end to the matter. Barbieri's argument that codes originated in life before any interpretation, which emerged later, highlights the need to investigate further the interpretative (semantic) component of interpretants. It is here that the work of Waddington, Goodwin, Thom, Piaget, von Foerster and Rocha can be drawn upon and used to support biosemiotics further. Integrating these concepts with the notion of anticipatory systems not only offers new directions for research but strengthens the claims of these theoretical concepts; the implicit assumption of teleology built into such notions as 'homeorhesis' and 'attractor' can be more robustly defended. When situated within this framework, it is possible to accept Barbieri's account of codes without interpretation, which if it is to be taken seriously as a mechanistic explanation must assume the validity of final causes that mechanisms serve, as part of a post-Newtonian ontology. Similarly, the concepts of mainstream complexity theorists (which Rosen saw as dealing only with 'complication') can be reinterpreted as part of a post-Newtonian ontology and biology, as Brian Goodwin argued, rather than being seen as another triumph of reductionist thought as Per Bak saw it. Anticipatory systems set the boundary conditions for fields in which patterns can emerge (at the edge of chaos) from large numbers of interacting components and be identified as patterns and responded to as such, rather than being seen as epiphenomena. Finally, structures like the self-regulating systems of transformations described by Piaget and those he influenced, which relate codes to the constructive, interpretative, pragmatic and semantic component of intepretants, can be recognized as a feature of at least multi-cellular life (Piaget, 1970, 3ff.; Rocha, 1996).

This integration of ideas through a tradition of post-mechanistic ontology provides the basis for a reassessment of and for charting new directions in physics. Von Neumann's suggestion that statistical concepts should be taken as original and that probability has priority over deterministic equations can be integrated into this synthesis. As Peirce argued, apparently law governed behaviour should be seen as emerging from a more primordial realm of chaos (which emerges from a state of absolute nothingness). Through chance, habits develop that reinforce themselves, generating entities with definite propensities and lawfulness in their behavior. These provide the conditions for semiosis. The deterministic models presenting nature as law governed are applicable to highly unusual situations, usually created artificially to eliminate random interactions. Like the measurements associated with such models, they should be appreciated as abstractions from a broader reality. This is how Schelling characterized Newtonian physics and it accords with Rosen's insights based on his study of modeling. While Rosen did not engage with the biosemioticians as did Pattee, his project of developing an ontology not only supports Pattee's contribution to this tradition in defending and explaining digital signs (symbols) and their role in organisms but justifies Hoffmeyer's complaint against Pattee that he still leaves us with a dualism in that we cannot describe the semiotic aspect of the world in the same language we use to describe its dynamic aspects (Hoffmeyer, 2008, 94). Rosen's ontology would have provided this unifying language and thereby also justify the role accorded by Hoffmeyer and Emmeche to analogue codes.

Brian Josephson has made a similar argument against the privileging of deterministic dynamical models of physics in developing Everett - Wheeler's suggestion for interpreting quantum physics. They argued that physical laws describable through equations emerge via the observer. Embracing Peirce's semiotics, Josephson argues that the gap between observer participancy and physical reality can be filled in by biosystems. Biology, Josephson argues, is primarily concerned with patterns and only secondarily with quantities; through the operation of signs, these patterns are forward looking. It is this capacity for anticipation that makes possible the kinds of observations that construct systems as law-governed (Josephson, 2012, 246). This delimits the domain of validity of what can be understood through an algorithm that from input data can determine which of the possibilities pre-stated in configuration space will be realized. Josephson's radical interpretation of quantum theory leaves room for the emergence of the unpredictable and incalculable novelty that clearly has occurred in the evolution of the biosphere. This not only breaks with Newton's physics, but also Einstein's physics and Bohr's physics, for as Stuart Kauffman pointed out, each of these prestates a configuration space (Kauffman, 2000, 123). This condition has hitherto (save for those influenced by Peirce or Whitehead) been taken as the defining feature of successful science. Such a suggestion coming from a leading theoretical physicist supports Rosen's contention that in any conflict with the discourse of biology it is the discourse of physics that should give way, and that the development of biology is the key to advancing physics.

8. Conclusion: Creating a New Mathematics

From what has been achieved in the past, we should get some idea of what research is likely to prove successful in the future. We can see that over the last two hundred years it has been the quest to develop a conception of being in terms of which the existence of life is intelligible and then developing the requisite mathematics that has been one of the most important driving forces, not only for biology, but also for mathematics and physics. This is likely to prove true in the future. As it was argued in 1975 by René Thom, it could again be argued that the stagnation in physics, recently complained about by Lee Smolin (Smolin, 2006), can be traced back to mainstream biology. The latter, dominated by the unimaginative tried and true methods and mathematics of reductionism, has largely abandoned the quest to make life itself intelligible. The consequent drying up of new insights into physical reality has crippled science as a whole. More importantly, since it is through what is understood of the world through science that societies model themselves and their relation to their environments and anticipate their future, this failure of science, foisting defective models of reality on whole societies, now threatens their very existence.

We can see a pattern in the history of biology and mathematics where theory inspired by and then guiding empirical work, work that aimed to characterize and comprehend life, stimulated efforts to develop mathematics adequate to the task, identifying, questioning and then transcending assumptions that had made life and mind unintelligible. This led to efforts to develop mathematics that went beyond describing motion from an external perspective and, instead of presupposing forms, could provide the means to model the processes of self-formation in nature. While this began with crystals, the aim was to develop mathematics able to deal with the much more complex processes of the self-formation of life. Since rejecting the externalist perspective meant seeing the development of human cognition as part of this self-formation of nature, particular attention was paid to the relationship between the development of mathematical concepts and the generation of forms in nature. The most basic mathematical concepts corresponded to virtually no order, while study of more specific concepts could make life intelligible and later, even the development of cognition. Inspired by this project, mathematics has advanced in two complementary directions. Firstly, there has been a push for greater abstraction to identify what is most basically essential in mathematical thought, thereby overthrowing often unconscious restrictive assumptions that limited the range of what was deemed comprehensible through mathematics. The second direction, correlated with the first, has been to examine the various conditions that are then conceivable, when mathematics is freed from the assumptions of particular conditions associated with classical physics.

The work of Hermann Grassmann illustrates the advance in two complementary directions. His constructivism amounted to 'the refusal to admit a domain of elements given prior to, or independently from the generation of the elements themselves … [It] is founded on the distinction between formal sciences – where no constraint on the domain is taken for granted, and the forms are one and the same with their construction – and real sciences, where some constraints are accepted from the outset, and forms are thus "embodied" in a fixed domain. … [A] general notion is particularized when further conditions are fixed, as in the case of the regressive product which is less general, if considered as relative to a unique domain' (Cantú, 100). His 'extension theory', essentially a universal geometric algebra and calculus, could accommodate the mathematics of Newtonian physics but opened up new possibilities, and was of such generality that it still provides a coordinating framework for and insights into modern physics. Implicitly, it accommodates and supports an ontology in which space is not assumed but can be seen as emergent so that it becomes possible to think about the origin and self-formation of the cosmos. Quaternions are just one example of mathematical ideas that could be interpreted through Grassmann's mathematics. As Clifford showed, extension theory provides insight into the special conditions associated with quaternions, but also suggests what other conditions might be possible and thereby what other features of reality might be modeled. The introduction of discontinuous signals and their derivatives by Heaviside, and then by Dirac in developing his formalism for quantum electro-dynamics, is another. Less directly, Grassmann's notion of multidimensional space also facilitated the development of phase space in which 3*n*-dimensional models of change gave insight into the nature of stability, instability, bifurcations, catastrophes, chaos and creativity at the edge of chaos. The two complementary directions in the development of mathematics are also evident in work unrelated or only tenuously related to Grassmann. Leaving aside the development of set theory and group theory, Hertz's introduction of and distinction between the notions of holonomic and nonholonomic constraints opened the way for the exploration by Pattee of non-holonomic constraints, clarifying the nature of symbols and what is involved in measurement and hierarchical control.

More recently, the development of Category Theory, focusing on and identifying common mathematical structures and clarifying the nature of modeling, has made it possible to study not only mathematical modeling of nature but modeling in nature by living systems. As Leo Corry pointed out, it was the development of the structural approach that gave a new impetus to Whitehead's effort, largely inspired by Grassmann, to develop a Universal Algebra. As Corry noted, 'it was not until the consolidation of the structural approach to algebra that a broader interest in such an undertaking became manifest' (Corry, 279).This has revealed the kinds of order that were ruled out of bounds by earlier mathematicians and thereby revealed new possibilities. Rosen's embracing of impredicativities is the most important achievement here, allowing mathematics to focus on relations to relations associated with reflexivity. As Rosen showed, these are required to model final causes, functions and anticipatory systems and therefore life itself. This in turn has provided further insight into semiosis as it was characterized by Peirce.

While advances in theory and mathematics are often made through efforts to clarify ideas, overcome incoherencies or reconcile different ideas in received work, the lesson from this history is that advances are most likely to be made when such efforts are combined with empirical research. If the work of different streams within the post-reductionist tradition of science are to be integrated and further developed, rather than being examined in relation to each other, the most promising path might be to look at living processes again and only through this try to develop such an integrated perspective. The central aim of the tradition of biological and mathematical thought originating in the work of Schelling is to comprehend nature as self-organizing and self-constructing. To bring this back into focus, one possible area of research that illustrates what could be done is the actual processes of organisms responding to their environments. There is much work in cognitive science now being reinterpreted in the broader framework of theoretical biology encompassing neuroscience examining such processes. Valuable and insightful as this work has been, it could also pay to examine areas where because of spatial and temporal scale and process rates it is easier to investigate. For such reasons Robert Ulanowicz defended ecology as the privileged domain and ultimate reference point for defining science (Ulanowicz, 1997, 6). However, given recent theoretical advances and empirical work in vegetative semiosis as described above, it is this kind of work that could prove a useful focus for reflection on what new directions mathematics could now take.

Günther Witzany's description of semiosis in plants indicates its complexity. Although Witzany conceived this semiosis as communication, his work has been interpreted as a development of biosemiotics and can be considered in relation to other work in the post-reductionist tradition. Although it focuses on plants, vegetative semiosis is common to plants, animals and humans and presupposes the semiosis of cells. Just as semiosis enables seedlings to discover new forms, so also with embryos. Rosen has justified the assumption by biosemioticians of final causes and the view that semiosis involves responding on the basis of models that organisms, including plants, have of themselves in their environments, that remember the past and anticipate the future. What Witzany is describing is how such models are achieved and the responses based upon them. Their achievement involves endosemiotics of considerable complexity, while responses involve specific kinds of growth or morphogenesis which involves at the same time niche creation. As such, growth is clearly constrained by what nutrients are accessible and what structures are physically possible, but is further constrained by the growing organism's assessment of its situation and of the best responses to make and by the dynamics of and semiosis within the ecosystem in which it is participating. Such assessments are complex because, for their achievement, different parts of the organism have to interpret and interact with each other and the future of both the plant and what is in its environment have to be anticipated. Clearly, this is an exemplary case of self-formation in nature, and comprehending this semiosis is precisely the knowledge from the inside called for by Schelling and his followers. Witzany referred to plants assessing their surroundings, making estimates, and achieving the optimum variant. Vegetative semiosis is really computing, although recognizing it as such expands the meaning of computing, and doing so could expand the meaning of mathematics.

As Pattee pointed out, there are different ways of understanding computing. The formal approach identifies computing with the manipulation of symbols and tends to presuppose the model of a Turing machine, even when hypothesizing that the whole of nature consists of such computing. This is merely the latest advance of the Newtonian view of the world. However, there is another way of understanding computing, 'computing in the wild', that treats such symbolic manipulation as a special case that ignores analogue computing which is iconic and indexical, the relationship between these two forms of computing, which might or might not be synchronous, and reflexivity in this computing (Pattee, 1995; MacLennan, 2004). Usually, those examining computing in the wild do not see it as a universal feature of nature but as a defining feature of life. In fact it is coming to be recognized that living is among other things computing in this sense, an insight eloquently captured by the title of Denis Bray's book, *Wetware*. There are a number of areas that have been identified where computing in the wild can be investigated: 'self-assembly, developmental processes, biochemical reactions, brain processes, bionetworks and cellular processes' (Dodig-Crnkovic, 2012). With the exception of brain processes, all of these are involved in vegetative semiosis as it was described by biosemioticians. The challenge is to comprehend this computing in the wild in all its complexity, avoiding the tendency to create a surrogate reality for life itself, then projecting one-sided models onto what is being studied – thus, merely reproducing what we already know from what has been learnt in the past about fractionated components of life.

In this regard it is necessary to ensure that terms that have ambivalent meanings are understood from a post-reductionist perspective and not a Newtonian perspective. For instance, one of the most problematic terms in biology is 'information'. Originally, inform meant to in-form, that is, to take in and be formed. The suffix '–ation' implies a noun of process, so 'information' originally meant to 'the process by which a form is being taken in and forming' someone. The notion of information as it was characterized by Shannon and Weaver has virtually none of this meaning, being defined in accordance with Newtonian thought (Brier, 2008). Gregory Bateson redefined information as 'a *difference which makes a difference*', able to make a difference because there are 'pathways ready to be triggered' (Bateson, 1972, 453). In this way it could be and was related it to living processes. Robert Rosen went even further in this direction, characterizing information as 'anything which is or can be an answer to a question' (1986, 174; 2012, 373), thereby highlighting the active nature of the response of an organism to the differences which makes a difference. We could heed Brian Josephson's Peircian argument that systems understandable through deterministic equations can only be properly understood in relation to living patterns characterized by semiosis. This would avoid the tendency to treat information reductionistically. The problem for mathematics is then to model this semiosis or computing in the wild in a way that does full justice to its holistic features.

Through the different strands of post-reductionist science such problems are being recognized, and efforts are being made to develop new forms of thinking and rethink the nature of both computing and mathematics accordingly. A boost to this whole program is coming from work in computer science, artificial intelligence and robotics where Newtonian assumptions have limited progress, despite the obvious significance of such research. Such limited progress has turned attention back to analogue computing and its potential and to quantum computing, and it is now recognized that specific forms of computing are best carried out in the medium being investigated. For instance, it has been shown that a combination of analogue computers and neural nets can identify the prime numbers in large numbers far faster than digital computers, and it has been proved by Leonard Adelman that a difficult Hamilton Path Problem could be solved using DNA computing in a week where it would take hundreds of years using the best algorithms and digital computers (Adelman, 1994; Nadin, 2010, 1). The promise of such work has led to alliances between theoretical scientists, mathematicians and researchers engaged in these more practical fields. The kind of work under way is illustrated by those involved in the integral biomathics project (Simeonov, 2010; Simeonov et.al., 2012). This is essentially revolutionary science, breaking with entrenched assumptions, and this highlights the further significance of their work.

Research in revolutionary science is more creative and thereby more unpredictable than normal science. It is less easy to manage. However, management science dominated by Newtonian thinking is now penetrating universities and research institutions previously wedded to the (Schelling-influenced) Humboldtian idea of the university and of research. (Gare, 2011, 27). Its proponents are foisting upon these institutions a defective model of their own identity, claiming thereby to be able to anticipate and improve their efficiency in the production of outputs for given inputs. However, there is no algorithm for generating creative thought or predicting it, and to attempt to quantitatively measure the quality of such thought is a category mistake. With their assumption that research can be predicted and efficiently controlled, managers influenced by such doctrines are hostile to revolutionary science and those who engage in it, despite work in the history of science showing that efforts to manage science in this way always destroy it (Ben-David 1971). The advance of Schellingian science and the incorporation of this in institutions and technology is required to free science from such ways of thinking, but this managerialism is by its very nature hostile to revolutionary anti-reductionist science. We are still grappling with the situation that Thom characterized in 1975 where, in the face of global environmental problems 'science [had sunk] into a futile hope of exhaustively describing reality, while forbidding itself to "understand" it' (Aubin, 2004, 95). We must hope that this revived quest to overcome the Newtonian paradigm will be more successful.

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