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Physical Basis for the Emergence of Autopoiesis, Cognition and Knowledge

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Knowledge is not passively received
but actively built up by the cognizing subject
(Ernst von Glasersfeld 1995: 18)

Abstract

Paper type: *Conceptual perspective.*
Background(s): *Physics, biology, epistemology*
Perspectives: *Theory of autopoietic systems, Popperian evolutionary epistemology and the biology of cognition.*
Context: *This paper is a contribution to developing the theories of hierarchically complex living systems and the natures of knowledge in such systems.*
Problem: *Dissonance between the literatures of knowledge management and organization theory and my observations of the living organization led to consideration of foundation questions: What does it mean to be alive? What is knowledge? How are life and knowledge related?*
Method: *The approach is synthetic and multidisciplinary. The concept of autopoiesis (as defined by Maturana) as a definition for life, and knowledge as a product of autopoiesis are developed from first principles regarding the behavior of dynamical systems in time.*
Results: *Autopoiesis and the construction of knowledge are inseparable aspects of physical phenomena scalable to many levels of organization (e.g., cells, multicellular organisms, organizations, social systems, etc.). The result unifies theories of epistemology, physical dynamics, life, biological evolution, knowledge and social systems.*
Implications: *Results highlight the importance to understand autopoiesis as first defined by Maturana and Varela – as a complex physical phenomenon persisting over time. Autopoietic "self-observation" is not paradoxical. As dynamic physical processes, any internal/external activities relating to "observations" are displaced in time. The worlds living systems act on are not those observed. "Circularly closed" systems are actually open spirals along the axis of time.*

Keywords: Complex dynamical systems, time, adjacent possible, natural selection, paradox, social systems theory

INTRODUCTION

Life scientists have not agreed on a consistent definition for what it is they study. As yet there is no generally accepted definition of life (e.g., Cleland & Chyba 2002; Oliver & Perry 2006; Tsokolov 2009). Oró (2002: p. 8) summarizes several definitions used by main stream biologists and lists ten properties that seem to characterize entities that we conventionally consider to be living (paraphrased here):

- Dynamic, self-organized, independent entities
- Made of water, carbon, hydrogen, oxygen, nitrogen, sulfur, phosphorus, often combined into organic molecules
- Exchange matter and energy with the environment
- Self-reproducing based on information stereospecifically translated from polymers
- Adaptable through mutation and evolution by natural selection.
- Catalytically self-regulated metabolism
- Cellular and multicellular organization and differentiation
- Organismic growth and asexual or sexual reproduction
- Irritability – dynamic responses to sensory stimuli
- May show consciousness, language, writing and technology.

Only a little thought will show that some of these characteristics are neither necessary nor sufficient to unambiguously differentiate between systems that at least some scientists would consider to be living and those that all would consider to be lifeless.

As will be well known to many readers of this journal, Humberto Maturana and his sometime student and colleague, Francisco Varela developed the concept of Autopoiesis in the 1970s (Maturana 1970, 1975, 1980, 1980a, 1980b, 2002; Maturana & Varela 1972, 1973; Varela 1979, 1980; Varela et al. 1974 – See Maturana 1991, 2002 for his view of the historical development of the idea) as a necessary and sufficient definition for what it meant for a system to be alive. Both studied medicine and biology at the Universidad de Chile and completed their PhDs at Harvard University on the neurophysiology of vision (e.g., Lettvin et al. 1959; Maturana 1958; Maturana et al. 1960; Varela 1970). Given their credentials in the physics and biology of vision and cognition, and the fact that the concept of autopoiesis was developed and phrased in such a way that could provide the basis for developing a unified theory of life and cognition, autopoiesis should have been widely considered by biologists as a candidate definition of life. Unfortunately, with the significant exception of the molecular biologist, P.L. Luisi (2003, 2006), the concept of autopoiesis has been virtually ignored in mainstream biology (e.g., neither Cleland & Chyba 2002, Tsokolov 2009, Oró or any other author in the Schopf book – see Oró 2002 – reference autopoiesis among the definitions of life they discuss).

On the other hand, Maturana (1980a) and a number of non-biologists, mainly in the social sciences, have applied autopoietic thinking to higher levels of organization such as human organizations and social systems (e.g., Zeleny 1977; Robb 1989; von Krogh & Roos 1995; Magalhaes 1998; Maula 2006). The most influential of these was Nicklas Luhmann (e.g., 1986, 1990, 1995) who developed a major following in his own right (e.g., see Bakken & Hernes 2003; Seidel & Becker 2005; Brier et al. 2007). More recently, from a biological point of view, I and colleagues have also applied autopoiesis to several levels of organization above the cellular (Hall 2003, 2005, 2006; Hall et al. 2005, 2007, 2010; Nousala & Hall 2008; Hall & Nousala 2010).

However, in later years Maturana (2002) changed his mind about the applicability of autopoiesis to higher levels of organization, and argued that autopoiesis was only properly applied to molecular systems at the cellular level. In addition to Maturana (2002), several workers (none of them biologists) have also argued that it is improper to apply autopoiesis to social systems (e.g., Mingers 1992, 1995, 2002, 2002a, 2004; Biggiero 2001; R. Kay 2001; Brocklesby 2004). Other non-biologists argued that autopoiesis is so poorly defined that it has little value for any purpose (e.g., Gaines (1980), Zolo (1990) and Swenson (1992, 1992a).

Many of these works come to their conclusions due to what I think are significant misunderstandings of Maturana and Varela’s original proposal. For example, as I will argue below, Luhmann and his followers based their interpretation of autopoiesis on misperceptions of what they thought was the fundamentally paradoxical nature of autopoietic self-observation.

My interest in autopoiesis derives from my experiences in two quite different careers: (1) As an evolutionary biologist with a strong background in physics and the generations of computer technology I completed my PhD studying speciation and evolutionary cytogenetics (Hall 1973, 2010), followed by two years postdoctoral work studying the epistemology of biology (Hall 1983). (2) From 1981 I found myself employed in a variety of industrial knowledge management roles (from 1990 to 2007 in Australia’s largest defense contractor – Hall 2001, 2003a; Hall et al. 2008; 2009). I only encountered Maturana and Varela’s work on Autopoiesis in 2002 as I was seeking to understand the roles and dynamics of knowledge in organizations from my rather unusual viewpoint as an evolutionary biologist managing engineering knowledge systems. Because I had already developed a heuristic definition of life in the late 1960s that was very similar to autopoiesis when teaching introductory biology courses (Hall 1966), I easily understood Maturana and Varela's concepts and its applicability to the kinds of organizational systems I was currently working with (Hall 2003).

From my viewpoint, one major reason why autopoiesis has not been well understood is linguistic difficulties with Maturana and Varela's highly paradigmatic writing. Both Maturana and Varela spoke English as a second language and were concerned by the recursive and seemingly paradoxical nature of the 'self-observation' that autopoietic systems require to self-maintain their autopoiesis. To describe and explore the concept of autopoiesis, the authors redefined and used many words in ways that were far removed from common usage. Mingers (1990: p. 570) notes that "Maturana develops his own language and there is little attempt to relate to already existing concepts and positions". The hermetic nature of Maturana's work on autopoiesis is borne out by the limited bibliographies of his papers. Most concepts in the paradigm are defined using other terms within this paradigm to form a largely recursive network of meaning, as can be seen by following definitions through Randall Whittaker's (2003) massive and highly useful Encyclopaedia Autopoietica. Few mainstream biologists would have the patience to immerse themselves in this hermetic language in an attempt to understand it.

Another reason biologists have not adopted the concept of autopoiesis as a basis for understanding life processes was the failure to develop a compelling logic within the paradigm of autopoiesis that accounts for the emergence and evolution of life, cognition and knowledge as we know them.

In this paper I will cross many disparate disciplines to show that autopoiesis does provide a compelling logic that accounts for the emergence and evolution of living systems at several levels of complexity. However, to see this logic clearly, autopoiesis needs to be considered in the frameworks of several independent paradigms: evolutionary epistemology, non-equilibrium thermodynamics, the emergence of order, the theory of hierarchically complex systems, and evolutionary biology. In applying these frameworks, the paradigmatic language of autopoiesis is related to other disciplines to show outsiders how autopoiesis helps to understand biological phenomena. I will explore some of the physical (e.g., Prigogine 1977; Morowitz 1968; Pattee 1995; Ellis 2006) and epistemological (Popper, 1972) foundations that underlie the emergence of autopoietic systems *as defined by Maturana and Varela*. Popper's work is particularly important, but as mainstream biologists have neglected the literature on autopoiesis, followers of Maturana in the disciplines of constructivism, cognitive science and second order cybernetics have neglected evolutionary epistemology for historical reasons largely irrelevant to the theoretical content of evolutionary epistemology. I will then introduce ideas from the theory of hierarchically complex systems to show how higher orders of autopoiesis based on systems of cells, multicellular systems, and multi organismic systems can easily emerge at still higher levels of biological organization.

AUTOPOIESIS

Maturana's quest to understand and define the phenomenon of life began in 1960 when a medical student asked him "What began three thousand eight hundred million years ago so that you can say now that living systems began then?" and discovered that he could not provide a clear definition for what it meant to be living (Maturana 2002: p. 6). Maturana and Varela (Maturana and Varela 1972, 1973, 1987; Varela 1979; Varela et al.

1974) coined the term 'autopoiesis' (*auto* = self + *poiesis* = production) to cover the list of properties they believed were necessary and minimally sufficient to define the property of life:

> An autopoietic machine is a machine organized (defined as a unity) as a network of processes of production (transformation and destruction) of components that produces the components which: (i) through their interactions and transformations continuously regenerate and realize the network of processes (relations) that produced them; and (ii) constitute it (the machine) as a concrete unity [i.e., distinguishable and definable entity] in the space in which they (the components) exist by specifying the topological domain of its realization as such a network. (Maturana and Varela 1973: pp. 78-79)

Varela et al. (1974) listed six criteria they considered to be necessary and sufficient conditions for recognizing a real-world system to be autopoietic, as paraphrased here. To be considered to be autopoietic, and thus living, the system must be:

- Bounded (“the unity [entity] has identifiable boundaries”). In this Maturana and Varela were primarily concerned that the entity could be discriminated by an external observer. To me this criterion should read, “the entity has self-identifiable boundaries”. Note: in living cells the boundary is a semi-permeable membrane.
- Complex (“there are constitutive elements of the unity, that is, components”)
- Mechanistic (“the component properties are capable of satisfying certain relations that determine in the unity the interactions and transformations of these components”). In other words, the complex entity is a dynamical system, such that components show causal interactions.
- Self-referential or self-differentiated (“the components that constitute the boundaries of the unity constitute these boundaries through preferential neighborhood relations and interactions between themselves, as determined by their properties in the space of their interactions”). That is, the boundaries of the system are structurally determined.
- Self-producing (“the boundaries of the unity are produced by the interactions of the components of the unity, either by transformations of previously produced components, or by transformations and/or coupling of non-component elements that enter the unity through its boundaries”).
- Autonomous (“all the other components of the unity are also produced by interactions of its components as in [the statement above], and … those which are not produced by the interactions of other components participate as necessary permanent constitutive components in the production of other components”).

It is not my purpose here to review Maturana and Varela’s definitions and explanation of autopoiesis in detail, as this is done very effectively by Whitaker (2003). However, key aspects of their definitions need highlighting to clarify linguistic difficulties and to show that the situations described in these statements are reasonable consequences of biophysical processes in the real world – i.e., that there is a compelling logic underlying autopoiesis as a necessary and sufficient condition for life.

Autopoiesis is a phenomenon of the physical dynamics of complex systems

In Maturana’s work, definitions of autopoiesis refer to the complex dissipative dynamics of physical systems of macromolecules in the real world (see also e.g., Maturana 1970: 9; Maturana 1978: 34; Maturana & Varela 1973: 81; Maturana 2002: 12):

> …[L]iving systems, as autopoietic systems in the physical space, must [structurally] satisfy the thermodynamic legality of the physical processes that demand that they should operate as materially and energetically open systems (in continuous material

> and energetic interchange with their medium). *In this context, the physical boundaries of a living system, as they are realized by its components through their preferential interactions within the autopoietic network, become apparent as surfaces of a thermodynamic cleavage*. (my emphasis - Maturana 1980: 54)

In other words, autopoietic systems are separated from the world by the consequences of their own self-determined internal dynamics without any requirement for structurally coupled “observers”.

Maturana and Varela (1973) apparently considered that there might be three orders of autopoietic systems, cells, “multicellulars”, and social systems. Maturana (1981: p. 22-23) observed that autopoiesis might also occur in other kinds of spaces, although the meaning is “space” in this context is not entirely clear (see Whitaker 2003: “space” and links from there):

> There is no restriction on the space in which an autopoietic system may exist. The physical space in which living systems exist is only one of many. In fact, living systems exist in the physical space as the space defined by their physical components. Accordingly, we have chosen to identify living systems with only autopoietic systems in the physical space because this is the space in which we exist, and because for that reason this space constitutes for us a peculiar limiting cognitive space. Otherwise the properties of autopoietic systems as autopoietic systems must be isomorphic in every space.

However, Maturana later concluded that autopoiesis could *only* exist at the molecular level of organization:

> [T]he molecular space is a space in which all the composite structures or systems that arise through the interactions of the molecules in it arise in a spontaneous dynamic molecular architecture without the guidance of any organizing force, principle, plan or information. There is no other domain like this in which the interactions of the elements that constitute it generate through their composition other elements of the same kind through thermal agitation and without external support. Hence I claim that neither the elements of the sub-molecular nor the elements of the supra-molecular domains can by themselves give rise to autopoietic systems as singular entities constituted as closed networks of productions of components that do not need external support to operate as such (Maturana 2002: p.14).

Autopoiesis requires “organizational closure”

Maturana (1970: p. 9) says life is a “closed causal circular process” that allows evolutionary change in the way the circularity is achieved but that cannot continue without that circularity. These concepts of closure and circularity are terms that have often been misunderstood by people citing Maturana and Varela’s works (see also Maturana 1980: p. 54; 1981: p. 30). Closure in Maturana and Varela’s writings is a difficult concept to define clearly. Whitaker understands “closure” (2003: “closure”) as follows:

> The quality or property of a descriptive network N such that one or another of the constituent elements of N (depicted or described as mappings onto N) interconnect wholly within the confines (explicit or implicit) of N itself. This circumscribes the set of constituent elements (or a collective designatum depicted through this set) such that its extent corresponds to the extent of N. In a complementary fashion, this circumscription induces (or is intended to portray) a circumscription of N itself on the basis of the depicted constituent(s)…. 'Closure' doesn't mean autonomous

systems are unresponsive; it only means that their changes of state in response to changes in their medium are realized and propagated solely within the network of processes constituting them (as they are defined). The difference has more to do with the way a system is defined than how that system (once defined) operates.

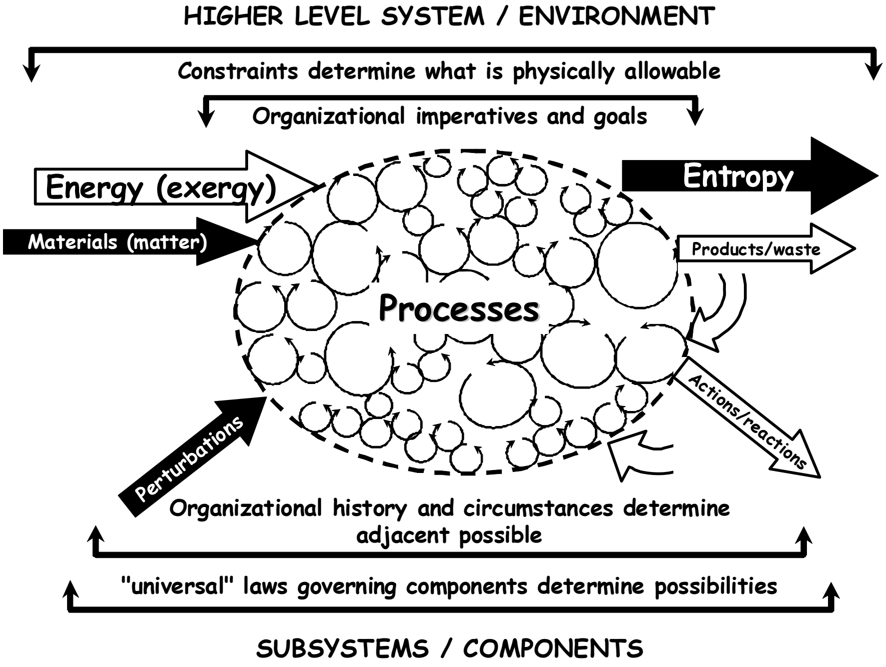

Figure 1. An autopoietic system in its environment (after Hall et al.).

To me, the key concept here is that the collection of interconnected processes as illustrated in Figure 1 involved in maintaining the autopoietic state continue to maintain those processes from one point in time to the next. This will be made clearer in the next major section.

The *apparent* paradox of self-observation

Maturana and Varela were both greatly concerned about the roles of observers in discriminating the existence of autopoietic systems. Historically, this concern has greatly confused discourse regarding autopoiesis. As I will show, given that autopoietic systems are, necessarily, "self"-defining systems, the only kind of "observation" that is important in the definition of an autopoietic system is "self-observation". In other words, we, as independent observers of an autopoietic system should observe how it defines itself. This raises the question, how can we observe our own autopoiesis?

Maturana and Varela both note that the various kinds of self-observational feedback in the maintenance of self-regulating autopoietic entities are "apparently" paradoxical. This is related to the seemingly paradoxical use of cognitive processes to study cognition. Whitaker (2003) details Maturana and Varela's usage of the term paradox (see "circularity – 2", "complementarity – 1", "fundamental circularity", "objectivity in parentheses", and "parenthesis"). It is my understanding that neither Maturana nor Varela thought that these "circular" processes were actually paradoxical. However, their writings around the issues of circularity are so recursively contorted that others, such as Nicklas Luhmann seem to have concluded that autopoiesis is viciously circular (Hall & Nousala 2010), e.g:

> …we need [paradoxical statements] when we have to distinguish different observers from each other or when we have to distinguish self-observations from external observation, because for the self-observer things may appear as natural and necessary, whereas when seen from the outside they may appear artificial and contingent. The world thus variously observed remains, nevertheless, the same world, and therefore we have a paradox. An observer, then, is supposed to decide whether something is natural or artificial, necessary or contingent. But who can observe the observer (as necessary for this decision) and the decision (as contingent for the observer)? The observer may refuse to make this decision, but can the observer observe without making this decision or would the observer have to withdraw, when refusing this decision, to the position of a nonobserving observer? [Luhmann 1995a: p. 80]

As I will show below, given that observation of any kind, including self-observation, is a causally dynamic process in the physical realm, there is no paradox involved. However, as briefly discussed by Hall and Nousala (2010), Luhmann's concerns with the paradox led him to reduce autopoietic social systems to organizationally closed networks of self-producing and intangible "communications" that somehow form organizationally closed networks of "communicative events" in an imaginary phase space orthogonal to the real world. In such social systems the physical people only provide the environment for the system and are formally separate from it (Mingers 1995: 141).

TIME, DYNAMICAL SYSTEMS, ENTROPY AND THE EMERGENCE OF AUTOPOIESIS

Maturana and Varela always considered autopoietic systems to be physical systems, whose dynamics must be subject to the laws of physics and thermodynamics. However, their writings did not emphasize physical dynamics and the temporal evolution of real dynamical systems as the platform on which the concept of autopoiesis should be logically built. To my knowledge, only Urrestarazu (2004) has explored this path in any detail. Maturana (2002: p. 11) stated the crucial logic from which the remainder of this paper flows, but again did not amplify these statements to give them the clarity they deserved:

> Historical processes occur moment after moment following a path constituted at every instant in the conservation of something that connects the successive moments in it, and around which all else is open to change. … [L]iving systems are historical systems … that … exist as singular entities in a continuous flow of structural change around the conservation of autopoiesis and adaptation. Accordingly, it is not change that makes biological evolution a historical process, but it is the phylogenic and ontogenic continuous conservation of autopoiesis and adaptation as the relational conditions around which all else is open to change. In these circumstances, what is primarily conserved in the history of living systems is living (autopoiesis and adaptation). And what is secondarily conserved are the different forms of realization of living through the reproductive conservation of different manners of realization of autopoiesis in the conservation of adaptation. (Maturana 2002: 11)

Maturana and Varela (1973) and Varela et al. (1974) exclude the capacity for reproduction and evolution that are often included in definitions of life from their definition of autopoiesis, noting that sterile entities such as worker bees and mules are clearly living. Unfortunately, from my point of view as an evolutionary biologist, it is also evident from their later works that neither author had a clear understanding of genetics or evolutionary theory (Maturana and Varela 1987; Maturana and Mpodozis 2000). In any event Maturana and Varela's limited approach to autopoiesis has led to a general neglect in attempts to understand the role of evolutionary time in relation to the physical sustainability of autopoietic systems (Hall 2005; Hall et al., 2007). As will be seen, considering the role of time leads to some interesting conclusions.

Time, dynamics and causation in the real world

Our understanding of the physical universe seems to be in a state of pre-revolutionary crisis today (Kuhn 1970; Smolin 2006). Arguably one of the least understood aspects of physics is time (Petkov 2009). Most physics today assumes a mathematically defined four dimensional relativistic spacetime that is suitable for time-reversible microphysical dynamics (but not dynamics at the quantum level). Einsteinian spacetime implies that the universe exists as a fixed block that only allows an impression of becoming, the passage of time, and free-will (Ellis 2006; Petkov 2009). A small minority of authors argue that the universe must be evolving from a fixed and immutable block of the past through an instant of becoming (i.e., the present) that continually progresses towards a future that only exists as possiblities (Smolin 1997, 2004; Ellis 2006; Sorkin 2007; Christian 2007; Tuisku et al. 2009; Ellis & Rothman 2010). Ellis (2006) calls this the "*evolving block universe*", or when quantum coherence/decoherence is taken into consideration, the "crystallizing block universe" (Ellis & Rothman 2010). This is the concept of time followed here because it is the only kind of time in which the concepts of emergence, decision, action and Darwinian evolution make physical sense.

Dynamics is a concept deriving from physical mechanics that describes how particles and systems change through time under the influence of forces and interactions. A dynamical system is an interconnected set of particles or components that *changes through time* as the result of causal forces that propagate through the components as one particle influences others, and so on. Urrestarazu (2004)[1] very precisely defines what this means in terms of autopoietic systems. In a causal interaction within a dynamical system,

> The mechanism responsible for cause-effect coupling between dynamical objects … is meant to exist as a causal influence of one object on another that [can be distinguished] as occurring in time…. a) [I]n the absence of any other cause-effect coupling between B and any other object different from A, the triggered transition in B does [not] occur before the occurrence of the triggering transition in A. AND; b) whenever objects A and B are in a specified state and a specified triggering transition in A occurs, the same triggered transition occurs … in B, within a finite time interval.

Many dynamical systems studied by physics are assumed to be deterministic in that they behave according to fixed rules where changes can be represented by a mathematical formalization that describes the time dependence of each component's position in an n-dimensional *state space* where each dimension corresponds to a degree of freedom. Basically, when parameters of a dynamic system are set to a point in the system's state space, the vector associated with that place in space points in the direction of the place in

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[1] Although Urrestarazu 2004 is not formally published, it is a penetrating analysis of the physical basis for autopoiesis with an excellent lineage. He is currently publishing a more detailed account in three parts covering similar ground (Urrestarazu 2011). Hugo Urrestarazu was a student of Maturana's at the University of Chile in the 1970's and a friend of Varela's. Hugo subsequently undertook postgraduate studies in solid state physics at University College, London and has worked as a software systems engineer.

phase space that will be occupied by the system in the next instance. A set of differential equations describing the dynamics of the system allows a vector to be calculated for each point in state space. As the system evolves from a particular point in state space through time, its changes of state follow the vector field.

The dynamical behavior of simple mechanical systems may be quite orderly. Movement of a certain part will cause other connected parts in the system to move in certain ways. Dynamical processes are driven to evolve temporally in directions that dissipate free energy as rapidly as possible (Annila 2010, 2010a; Mäkelä & Annila 2010). However, even very simple deterministic mechanical systems such as a double pendulum may exhibit chaotic dynamics if the interactions among the components are nonlinear (i.e., where changes in the system are described by two or more variables, and are thus not directly proportional to incremental changes in a controlling variable or time). Complex nonlinear systems exhibit *chaos* if they are sensitive to initial conditions whereby solutions diverge to apparently random states after a time. Such systems are computationally intractable, in that their state at a particular time cannot be modeled in fewer steps than required to reach that state. At smaller scales, system dynamics becomes even less predictable when quantum indeterminacy begins to affect outcomes. How, then, can we describe the autopoiesis of a complex non-linear system whose internal particle dynamics may be affected by quantum indeterminacy?

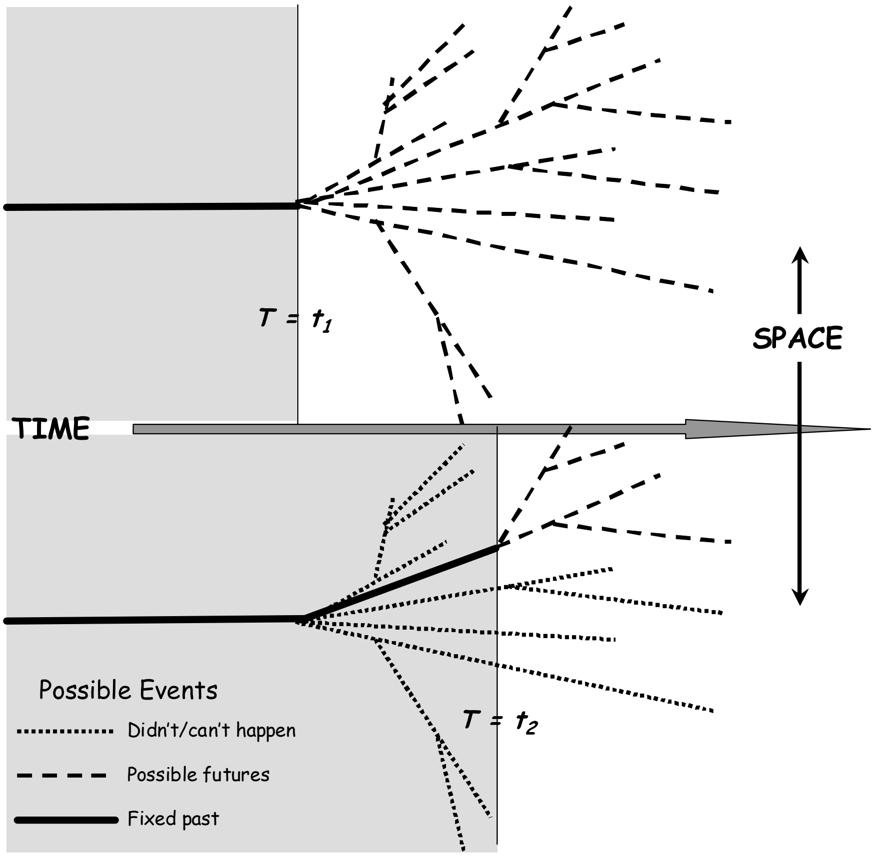

Figure 2. System trajectories in a non-deterministic space time (after Ellis 2006; Ellis & Rothman 2010).

Figure 2 illustrates possible trajectories in state space of a physical system at two points in time, t_1 and t_2 with time progressing from left to right. The grey areas represent the block universe of time past, with the white area the as yet undetermined future. The line dividing the past and future is “now”, the instant of becoming as dynamically produced from the prior instant. Historical events in the fixed past are shown by the solid line. States that are possible to reach in the next instant when now = t_1 are indicated by dashed lines. Kauffman (2000, 2003; Kauffman et al 2008) calls these states the “*adjacent possible*”. In our perceived universe, only one of the adjacent possible states is realized; in a multiverse as described in the “many worlds” theory of quantum mechanics every possible state is realized on different worldliness branching away from now (Deutsch 1997; 2002; Wallace 2010) – each of which contains a consciousness that is unaware unaffected by any of the other worldlines. Note that when a later instant, t_2 is reached, the once possible states along worldliness that didn’t happen are no longer possible in the universe of any particular worldline. As will be seen after the next illustration, the effect of time’s pruning of the adjacent possibles has profound implications for understanding autopoietic systems.

Structural knowledge and the emergence of self-producing entities in toy universes

Cellular automata (Weisstein 2010) are computational artifacts that powerfully illustrate some important concepts relating to self-producing systems. Cellular automata consist of a 1, 2, or more dimensional lattice of "cells", where each cell can have any one of a finite number of states. In most implementations, the states of all cells in the lattice are updated simultaneously in a progression of discrete time “steps”. The state of each cell in the lattice is determined according to some rule which may depend on the state of the cell and its neighbors at the previous time step. These are “toy universes” where the nature of “space” and the rules of the game (i.e., laws of nature) are controlled by the user.

Conway’s Game of Life (2010) – “GoL” is a well known cellular automaton based on a two-dimensional grid in which dynamically self-producing entities can exist. Self-producing entities with cyclical dynamics, such as the simple “glider” illustrated in Figure 3 emerge from the computational evolution of some types of patterns established to initiate or “seed” the calculation (Gotts 2009). GoL and related cellular automata can easily be explored in the freely downloadable tool Golly[2]. Note: given GoL’s rules, even though it may be impossible to model with a compact algorithm, the temporal evolution of any seeded pattern is completely deterministic. Most seeds evolve to empty, static or stabile states. In a few, dynamically self-producing, coherent and mobile simple entities such as “gliders” and more complex extended “ships”, and “engines” emerge and progress away from the original seed Gotts (2009). Note that the “knowledge” for such self-production is embodied purely in the instantaneous structure of the automaton as driven by the rules of the game (i.e., laws of the toy universe). Because at T_1 the automaton has the structure shown in 1-1, at T_2 the rules produce the structure at 1-2, and so on until the cycle begins to repeat at T_5 . Gotts documented the emergence of complex entities cycling over some 90 steps or more, such as “puffer trains” and “switch engines” that can perturb one another via gliders and debris they generate. In many cases when a dynamic entity is perturbed by interaction with a glider or debris, it disintegrates and “dies” or turns into incoherent stationary debris. However, Gotts has observed the emergence of particular dynamic structures that can compensate for or mutate and survive as a slightly altered dynamic structure, and has established that scenarios exist with the capacity for the open-ended evolution by natural selection of increasingly robust entities. In Maturana and Varela’s words,

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[2] The Golly software is freely downloadable from http://golly.sourceforge.net/.

> there may be many different kinds of autopoietic machines in the physical space (physical autopoietic machines); all of them, however, will be organized in such a manner that any physical interference with their operation outside their domain of compensations will result in their disintegration: that is, in the loss of autopoiesis. It also follows that the actual way in which the autopoietic organization is realized in one of these machines (its structure) determines the particular perturbations it can suffer without disintegration, and hence, the domain of interactions in which it can be observed. (Maturana & Varela 1973: 81)

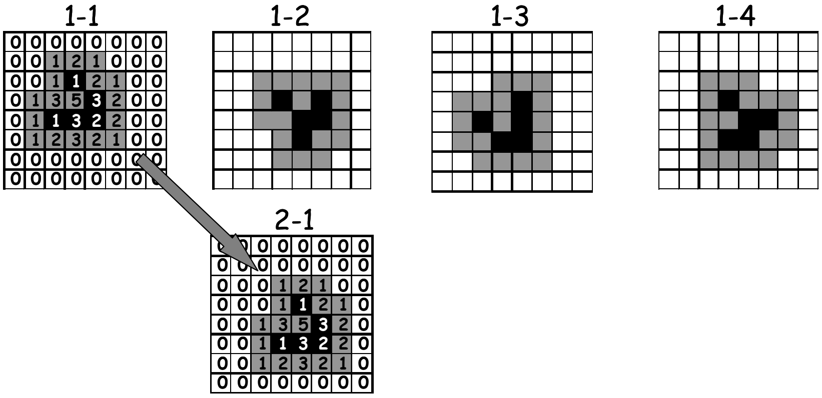

Figure 3. A cyclically self-producing "glider" in Conway's Game of Life. "Active" cells are black, "inactive" cells are empty and inactive cells involved in producing the glider are gray. The cycle and step number are shown above each grid. A number in a cell indicates the number of active cells touching the numbered cell. Conway's Life is a binary cellular automaton in a two dimensional grid where the next state of each lattice cell depends only on its own state and the sum of the states of the cells it touches. The governing rule states that: (1) An inactive cell with exactly three active neighbors becomes active; (2) An active cell with two or three active neighbors remains active. (3) Cells with other than two or three active neighbors become or remain inactive. The arrow indicates that every four steps the glider moves on the grid diagonally downward by one row and to the right by one column in a repeating cycle. (After Beer 2004).

Cellular automata visualized on a computer screen represent virtual worlds existing only as abstractions in a computer memory. However, very similar self-producing entities can exist in the physical world (e.g., Kauffman 1983; Luisi & Varela 1989). Here, the "knowledge" for autopoietic self-production is also embodied in the instantaneous physical organization of the entities' components in relationship to their three dimensional spatial environments such that the autopoietic organization is causally imposed from the component's configurations in the state space of one instant to the state space of the next instant as the system state steps from one instant to the next..

The second law of thermodynamics and the emergence of autopoietic knowledge

Unlike cellular automata living in a deterministic virtual world, systems existing in a physical world are subject to the laws of nature, especially including those of thermodynamics.

> Nothing is said in the characterization of living systems as autopoietic systems about the operational constraints under which their autopoiesis must be realized. This is because whatever constraints must be satisfied, they are determined by the properties of the components, and they are implied when it is said that an autopoietic system exists in the space in which its components exist. Thus, *autopoietic systems in the physical space must satisfy thermodynamics and must be materially and energetically open, even though they are necessarily closed in their dynamics of states*. (Maturana 1981: p. 22).

In other words, autopoietic systems are subject to the laws of physics and that their causally driven dynamics must necessarily involve dissipative energy transformations as energy is physically transported from sources of high potential to sinks of lower potential.

Dissipative dynamic processes involved in transporting fluxes of energy selectively favor the emergence of increasingly ordered cyclical structures or systems such that it is likely that chemical systems involved in the transport will be driven to states of increasing complexity resembling metabolism (Prigogine 1945, 1955, 1977; Morowitz 1968; Kay 1984, 2000; Schneider & Kay 1994, 1997; Kauffman 1983, 2000; Chaisson 2001; Corning 2002; Salthe 2004; Sharma & Annila 2007; Annila 2010, 2010a; Annila & Annila 2008; Annila & Salthe 2010). Selection will favor dissipative systems that are stabilized by feedback regulation. Morowitz (1968: p. 120) said, “The existence of cycles implies that feedback must be operative in the system. Therefore, the general notions of control theory [cybernetics] and the general properties of servo networks must be characteristic of biological systems at the most fundamental level of operation". As the causal dynamic structure propagates from one instant to the next, each instant’s structure is constrained by its historical lineage to remain within the adjacent possible allowed by the structure of the previous instant. As demonstrated in the toy universe above, this represents a form of embodied “knowledge” or “control information” (Corning 2001) relating to structural configurations that worked in the past. If a perturbation sufficiently disrupts the instantaneous structure of causally coordinated system such a way that its cyclic organization is forced onto a world-line that leads to dis-integration into uncoordinated debris, whatever knowledge was embodied in the propagating system to that instant is lost (Gotts 2009)[3]. On the other hand, if the system successfully compensates for the particular kind of perturbation, structure enabling this success will be included in the historical sequence of coordinated structures propagating from one instant to the next. As will be detailed in the next major section, this is basically a process of “trial and error elimination” (Popper 1972;) or “blind variation and selective retention” (Campbell 1960, 1974) that gradually increments the system’s embodied knowledge contributing to its survival capacity.

Thus, as long as energy continues to flow through any dynamically self-producing system that maintains its coordinated structure through a sequence of instants its knowledge of the world is bound to increase as described in the next section.

Physical considerations for the emergence of knowledge

The work of the biophysicist, Howard Pattee is particularly seminal in understanding the physical meaning of knowledge[4]. The key to understanding the origins of autopoiesis is to understand where and how the complex system comes to discriminate 'self' from non-self and acquires the capacity to control the self. Howard Pattee in a series of works beginning in (1961) has explored these fundamental questions from a viewpoint beginning in biophysics and biochemistry (Pattee 1968, 1969, 1972, 1972, 1973, 1977, 1982, 1995, 1995a, 1996, 1997, 2000, 2001, 2001a, 2005, 2006, 2007, 2007a, 2008,

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[3] Note: these kinds of dis-integration events can be visualized on the Golly platform (see note 2) in Game of Life or other related cellular automata where dynamically self-producing entities such as “spaceships” or “engines” are perturbed by collisions with stationary debris or other dynamic entities such as gliders.

[4] Pattee, in turn, bases his work to some extent on the metaphysical semiotics of Charles Stanford Peirce (b. 1839 – d. 1914). However, here, I am particularly concerned with the concrete physics of Pattee’s approach to the physical basis for knowledge and information.

2009). His student, Luis Rocha extended the work on cellular automata (Rocha 1997, 1998, 2001; Rocha & Bollen 2001; Rocha & Hordijk 2005).

Pattee (1996) introduces the concept of *epistemic operations*, which include biological functions like observation, detection, recognition, measurement and control that he considers differentiate living things from non-life. Defining this set of terms at this point presupposes that we already have a clear understanding of how these concepts follow from physical processes in the autopoietic framework. For this reason, we will accept them for now as 'primitive', and allow their physical definitions to emerge from the development of the paper.

Pattee also uses three important epistemological concepts in developing his concept of epistemic operations may be relatively unfamiliar. Like Maturana and Varela's writing, Pattee's writing tends towards circularity in its definitions. Following are my interpretations of these terms. All assume the involvement of an observer and that which is observed.

Epistemic cut

Pattee uses “epistemic cut” 1995a, 2001, 2001a, 2005, 2007, 2008 in reference to the strict ontological separation (in physical and philosophical senses) between:

> *knowledge of reality* from *reality itself*, e.g., description from construction, simulation from realization, mind from brain [*or cognition from physical system*]. Selective evolution began with a description-construction cut.... The highly evolved cognitive epistemology of physics requires an epistemic cut between reversible dynamic laws and the irreversible process of measuring initial conditions. This is also known as the measurement problem. (Pattee 1995a).

The epistemic cut is also known as the “*Heisenberg cut*” (Graben & Atmanspacher 2009), that relates to Wolfgang Pauli’s (1950, 1952) principle of complementarity. Abel (2008) defined the related concept ‘*cybernetic cut*’: “The dynamics of physicality (‘chance and necessity’) lie on one side. On the other side lies the ability to choose with intent what aspects of ontological being will be preferred, pursued, selected, rearranged, integrated, organized, preserved, and used (cybernetic formalism).” As will be discussed in more detail below Abel argues that the latter is required for an emergent system to be considered to be living.

On the other hand, there is little similarity to the “*epistemic gap*” separating “phenomenological knowledge” from “physical knowledge” (Alter & Walter 2006; Chalmers 2006). Not only are the paradigms surrounding the “cut” and the “gap” quite different, but epistemic gap relates to forms of human consciousness, not fundamental aspects of living things. Pattee’s “cut” relates to the ontological difference between uninterpreted physical reality on one side and information about that reality on the other side, i.e., the cut is between physical reality and knowledge of the physics. This is confirmed by Pattee’s sources for statements of the idea: Cassirer (1957), Harnad (1990), Planck (1960), von Neumann (1955), (1966), and Whitehead (1927) , who are considering the question from physical rather than psychological, philosophical or metaphysical points of view.

What “epistemic cut” means depends on Pattee’s definitions of information and knowledge:

> **Knowledge** is potentially useful information *about* something. **Information** is commonly represented by *symbols*. Symbols *stand for* or are *about* what is represented. Knowledge may be about what we call reality, or it may be about other

> knowledge. It is the *implementation* of "standing for" and "about" - the process of executing the epistemic cut - that [we need] to explore.
>
> Heritable, communicable, or objective knowledge requires an epistemic cut to distinguish the knowledge from what the knowledge is about. By *useful* information or knowledge I mean information in the evolutionary sense of information for construction and control, measured or selected information, or information ultimately necessary for survival. [my emphasis, his italics]. …
>
> The requirement for heritable or objective knowledge is the [epistemic] separation of the subject from the object, the description from the construction, the knower from the known. Hereditary information originated with life with the separation of description and construction.... Von Neumann ... states this epistemology of physical theory clearly: ‘ … we must always divide the world into two parts, the one being the observed system, the other the observer. The boundary between the two is arbitrary to a very large extent … but this does not change the fact that the boundary must be put somewhere, if the method is not to proceed vacuously …’ In physical theory, the observer is formally related to the observed system only by the results of measurements of the observables defined by the theory, but the formulation of the theory, the choice of observables, the construction of measuring devices, and the measurement process itself cannot be formalized. ...
>
> … [L]aws and initial conditions alone are not enough to make a complete physical theory that must include measurement. Measurement and control require a third category of knowledge called boundary conditions or constraints. These are initial conditions that can be compressed *locally* but that are neither invariant nor universal like laws. When such a constraint is viewed abstractly it is often called a rule; when it is viewed concretely it is often called a machine or hardware.
>
> Both experience and logic teach us that initial conditions cannot be *measured*, nor boundary conditions *constructed*, with the deterministic precision of the formal dynamical laws. This uncertainty requires a third category of knowledge we call *statistical laws*. Statistical laws introduce one of the great unresolved fundamental problems of epistemology. The dynamical laws of physics are all symmetric in time and therefore reversible, while statistical laws are irreversible. (Pattee 1995a: pp. 26-27)

Pattee (1997, 2001), Rocha (1998, 2001), and Rocha and Hordijk (2004) discuss biophysical implications of coding that segregates knowledge from system dynamics. It should also be noted that the physical requirement for an epistemic cut seems to require a separation between the body and mind.

Varela & Maturana (1973) highlighted the existence of an epistemic cut (without defining a specific term for this relationship) between physical reality and system “structure” (i.e., “there seems to be a hopeless gap between the way in which a Turing machine is defined and any possible instance (electrical, mechanical, etc.) of it.” - 1973: p. 379). They also called the cut “a disjunction between materiality and structure”. Varela and Maturana discussed the nature of the cut from the point of view of an external observer, but neither here nor in their other writings do they elaborate this idea as Pattee did or follow it up from a point of view focused on control information.

Semiotic control.

(Pattee 1997) refers to the situation where symbolically encoded information is used to control a physical process as semiotic control. In other words there is an epistemic cut between the control information and that which is controlled that is the reciprocal to the kinds of cuts cited immediately above (see Corning’s 2001, 2002 *control information*).

By contrast to physical laws that are global and inexorable, controls are local and conditional. According to Pattee (1997):

> Physical laws and semiotic controls require disjoint, complementary modes of conceptualization and description. Laws are global and inexorable. Controls are local and conditional. Life originated with semiotic controls. Semiotic controls require *measurement*, *memory*, and *selection*, none of which are *functionally* describable by physical laws that, unlike semiotic systems, are based on *energy*, *time*, and *rates* of change. However, they are *structurally* describable in the language of physics in terms of nonintegrable constraints, energy degenerate states, temporal incoherence, and irreversible dissipative events.

Local and conditional control is determined by the historically developed instantaneous structure of the physical ensemble including both what is controlled and what is providing the controlling constraints. Control is an effect of the instantaneous dynamics of the structure of local situation as this constrains the possibilities allowed by universal law.

Still following Pattee (1997), at its core, universal physical laws do not include a capability to control. These specifically relate to situations where there is no control. where the relationship between cause and effect "is invariant with respect to different observers, and consequently those relationships between events over which the observer has no control." For control to exist, the 'controller' [which may be no more than the instantaneous local ensemble itself] must be able to provide some form of local circumstances or local structural constraint (which may be positive or negative) in addition to what is dictated/expected by universal physical law.

Semantic closure

Similarly to organizational closure, semantic closure provides a connection between the semantic/cognitive processes of recognition, measurement and decision and the application of constraints (controls) to the physical world. Semantic closure:

> [i]s an extension of von Neumann's logic of description and construction for open-ended evolution. Semantic closure is both physical and logical, and it is an apparently irreducible closure, which is why the origin of life is such a difficult problem. [Pattee (2000)]

Semantic closure refers to the situation where there is a cyclic process of self-reference between the material and symbolic aspects of the organism relating (1) to the physical processes of observation and detection, (2) the semantic processes of recognition, measurement and decision, (3) the physical application of semiotic controls, and (4) observation of the results of that application to begin a new cycle. Semantic closure is presumably what Maturana and Varela were trying to express in their concept of "circular" closure.

Crossing the chasm

These definitions are useful, but Pattee (2000) did not see a clear path by which semantic closure could evolve from an unthinking world of purely physical processes to self-producing life. Abel (2008, 2009, 2010) following on from Pattee argued that cybernetically controlled “intent” had to be present for an emergent system to be considered to be living. The meaning of this cut depends on what Abel means by "*cybernetic formalism*", which seems to boil down to formal rules encoded in the genome. Abel (2008: p. 260) concludes that the cybernetic cut is a chasm that has not and cannot be crossed, and lists three tests where the falsification of any one of them would falsify his claim:

1. No nontrivial computational function will ever spontaneously arise in any inanimate physicodynamic medium or environment independent of formal intervention and controls.
2. No sophisticated algorithmic optimization will spontaneously proceed in any inanimate environment upon removal of hidden experimenter choices and steering of iterations.
3. No nontrivial functional controls of inanimate physical phenomena will be realized independent of the programming of dynamically-inert (dynamicallyincoherent) configurable switches that alone instantiate formal agent choices into physical reality.

To summarize, in what seems to be a paradox, physical autopoietic systems (W1) cannot exist without cybernetic control information; and knowledge (W2) cannot exist without its formation in autopoietic systems. In today's world, all organic life (i.e., single and multi-celled organisms) is characterized by highly complex systems of heredity based on the machinery of DNA replication, transcription of DNA into RNA, and the translation of RNA into structural and regulatory proteins. In this system DNA carries hereditary knowledge expressed in an arbitrary code of nucleotide sequences (W3), where the encoded knowledge persists down through many generations of physical replication and can be shared between individuals. This raises the question as to how such a complex system could have emerged from the structural knowledge of primitive autopoietic systems and will lead to solution to the body-mind problem.

Although we can never know the history of this emergence in detail, I think a plausible pathway can be constructed from what we know about the biochemistry of organic life as constrained by the theory of knowledge-based autopoietic systems developed above.

Key question: what is embodied knowledge and where does it come from?

Prigogine, Kay, Schneider, Maturana, Varela, and Pattee provide the phenomenological and epistemological framework for considering the emergence of knowledge-based complex systems. It now remains to explore specific conditions for the emergence of the necessary capabilities for self-control required for the existence of autonomous autopoietic systems.

From the prior discussion it should be clear that the key issue is to account for the origin and nature of the self-regulatory control information an autopoietic entity uses to maintain homeostasis of the system containing the control information. Given the extreme complexity and specificity of the apparatus required to replicate and assort hereditary information encoded in DNA molecules, and given that the phenomenon of autopoiesis must reasonably be assumed to have emerged from the near equilibrium of an unorganized chaos, following Rizzotti (1994) the first plausible autopoietic systems would have been very much less sophisticated.

To us the key feature not considered sufficiently by Maturana and Varela for identifying an autopoietic system is that the system must maintain some of its 'self' with functional integrity *through a passage of time* in the face of external perturbations. Survival through time implies that the homeostatic system must have some properties of its structural organization that provide negative feedback control to counteract perturbations that would otherwise lead to disintegration. The primordial autopoietic system would have coalesced as autocatalytic sets close to thermodynamic equilibrium as demonstrated in several biochemical and computational models (Kauffman 1983, 1995) through a spontaneous emergences of simple structural mechanisms to transport and dissipate fluxes of exergy. However, to survive changing circumstances a nascent system must be so structured that at least some exergy is fed back into the system to maintain its integrity and provide a reserve to compensate destabilizing perturbations and fluctuations in the medium as environmental equilibria move away from those supporting the system's initial coalescence.

KARL POPPER'S EVOLUTIONARY EPISTEMOLOGY, AUTOPOIESIS AND THE ORIGIN OF KNOWLEDGE

Karl Popper's (1972, 1974, 1977, 1978, 1982, 1987, 1994, 1999; Popper and Eccles 1977; Campbell 1974; Niiniluoto 1999; Munz 2004) evolutionary epistemology, combined with the physics of dynamical systems provides a compelling foundation for accepting autopoiesis as fundamental definition of life as a unifying principle for epistemology, the life sciences and social sciences and the broad range of disciplines concerned with information and knowledge.

Unfortunately, Popper's seminal thinking about the emergence of knowledge and cognition has been almost completely ignored by the disciplines concerned with autopoietic cognition and constructivism. According to Popper's student, Bartley (1982), many professional philosophers disapproved Popper's (1959, 1963) early works on fallacy of inductive reasoning and the problem of demarcating between science and myth. This was exacerbated by significant and seemingly bitter personal disagreements between Popper and Wittgenstein (Edmonds & Eidinow 2001; Munz 2004) and Popper and Michael Polanyi (Watkins 1997), such that neither Wittgenstein or Polanyi, nor in most cases their students, cited Popper's works. Given that Wittgenstein and Polanyi (e.g., 1958, 1966) are often cited as epistemological sources by cognitive scientists and constructivists, few, including Maturana or Varela seem to have considered Popper's later epistemological works.

For example, the only citation to Popper I have found in Maturana's works is in his (1991a) discussion of scientific and philosophical theories is to Popper's first book (1959). Even Riegler's (2006) comparison of constructivist and evolutionary epistemologies cites Popper only once, for a work (1963) that predates Popper's important publications on evolutionary epistemology[5]. Finally, a Google search of the journal Constructivist Foundations as at 27 December 2010 [Popper site:http://www.univie.ac.at/constructivism/journal/] yielded only 11 unique articles referring to Popper. Of these 5 mentioned Popper by name but did not cite specific works. Only two papers cited Popper (1972) or later works (Mitterer 2008; Gadenne 2010). None of the papers Popper's evolutionary epistemology. Thus, I find no evidence that considerations from Popper's evolutionary epistemology have been incorporated in autopoietic or constructivist thinking. In this section I will show the synergism between Maturana's autopoietic constructivist approach to cognition and Popper's constructivist approach to evolutionary epistemology forms a compelling basis to unify epistemology, physics, biology, the cognitive and organizational sciences.

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[5] On the other hand, in developing his idea of the "ratchet effect" as a fundamental principle in the constructive processes of evolution and cognition, Riegler (2001) cites Popper (1972).

Also, as is the case for the absence of fruitful exchanges of ideas between constructivism and Popperian evolutionary epistemology, I have found no evidence for cross linkages between Howard Pattee's thinking and either of the previous mentioned schools. The following section unifies the three epistemologies.

Popper's constructivism and ideas regarding the nature of knowledge in his later works.

Although Popper studiously avoided giving explicit definitions to terms (apparently seeing this as engaging in Wittgensteinian "word games), from his usage in and post (1972) that "*knowledge*" is used in the sense of "claimed or actual solutions to real world problems of life". Arguably, except for Popper's stress that cognizing beings survived or died in a *physical world that existed independently from their cognition* (i.e., the "real" world), in his later years Popper was essentially a radical constructivist (this is "radical" in the sense of being an uncompromising constructivist - Glasersfeld 2005):

> …the "radical" conclusion [is] that the role of knowledge is **not to reflect an objective reality** but to empower us to act effectively in the world of our experience, which is to say, to act so that we achieve a goal we have chosen [i.e., to solve a problem of life!]. Hence the axiom that knowledge must *fit* reality but does not represent (Glasersfeld 1996: p. 283 – his italics, my emphasis).

At the core of all Popper's epistemological writings is his understanding that all claims to knowledge are fallible in that we can never prove the truth of our claims to know the truth of the world. In other words, Popper claims that all knowledge is subjectively constructed on the basis of the living systems interactions with the world, and does not exist as images, copies or *reflections* of reality onto a receptive mind. Popper makes this crystal clear in his (1972) book, "Objective Knowledge: An Evolutionary Approach". Unfortunately, most constructivists who have cited Popper (e.g., Glasersfeld 1996) have probably grossly misunderstood Popper's use of the world "objective" in the title, (i.e., due to paradigmatic incommensurability - Kuhn 1970, 1982) such that the book's content has been neglected. To Popper, in his later works, "objective knowledge" is *not* ever considered to be a reflection of the "objective" world, but rather *knowledge that has been codified into/onto a format that has an objective existence independent from the subjective cognition of a living being*, such that it may be decoded and criticized at some other time and place by other beings. To make the meaning clear:

> Only objective knowledge is criticizable: subjective knowledge becomes criticizable only when it becomes objective. And it become objective when we can *say* what we think; and even more so when we *write* it down, or *print* it. (Popper's italics - Popper 1972: p. 25)

Popper does not claim that objective knowledge has any direct connection to true reality. In fact, as I understand Popper, his "objective knowledge" is exactly that referred to by Pattee (1995a: p. 27)

> The requirement for heritable or *objective* knowledge is the [epistemic] separation of the subject from the object, the description from the construction, the knower from the known. Hereditary information originated with life with the separation of description and construction.

The evolutionary construction of knowledge

Although Popper retained his (1959, 1963) arguments that claims to universal truth can be deductively falsified in logic, in and after (1972) he accepts that falsification in the real world is little better that confirmation because a falsified claim can still be rescued by an infinite regress of auxiliary hypotheses to explain away the falsification. Popper's (1972) and subsequent constructivist approach to evolutionary epistemology is most often summarized in what he called the "tetradic schema", i.e., $\boldsymbol{P_1} \rightarrow \boldsymbol{TT} \rightarrow \boldsymbol{EE} \rightarrow \boldsymbol{P_2}$, where $\boldsymbol{P_1}$ is a problem to be solved by a cognizing entity, ***TT*** are subjectively constructed tentative theories put forth as possible problem solutions, ***EE*** "is the process of error elimination to which … theories are exposed (natural selection on the pre-scientific level; critical examination, including experiment, on the scientific level), and $\boldsymbol{P_2}$ is the new problem which emerges from exposing the errors of our tentative theories" (Popper 1963 [addendum no. 8 added in Ed. 3 – 1969; Ed. 4, 1972: p. 407]). The "pre-scientific" version of the tetradic schema applies to all kinds of living organisms – i.e., simple autopoietic systems, where entities embodying and enacting an erroneous "theory" die (or at least don't reproduce), such their attempted problem solution is lost with their dis-integration. Those that survived either weren't tested or held an adequate theory that allowed them to survive the test, demonstrating that their problem solution was better than those that died. The "scientific" version of the tetradic schema is available to self conscious entities able to articulate their tentative theories in forms that can be criticized and tested experimentally. This allows erroneous hypotheses to be killed conceptually in lieu of having them removed by the death of their carriers. This concept was first published in (1966) together with a more elaborate version he termed his "general theory of evolution" (Figure 4).

Popper "general theory of evolution" is expressly intended to apply to "all organisms" (1966 [1972: pp. 241-244]). His discussion of "plastic controls" corresponds to what is known by evolutionary biologists as the "Baldwin effect" (Simpson 1953; Jablonka & Lamb 2004). However, what evolves as knowledge grows will be clarified in the next subsection.

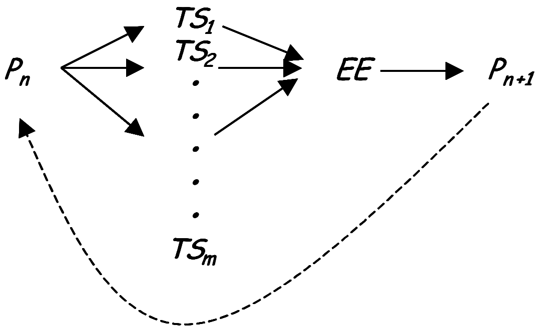


Figure 4. Popper's "general theory of evolution" (From Hall 2005, after Popper 1972: pp. 243). $\boldsymbol{P_n}$ is a problem situation the living entity faces in the world, $\boldsymbol{TS_m}$ represent a range of tentative solutions the entity may attempt or propose in order to solve the problem. ***EE*** represents a process of criticism and error elimination that selectively removes those solutions that don't work in practice. $\boldsymbol{P_{n+1}}$ represents the now changed problem situation remaining after a solution has worked. As the entity iterates the process (the arrow indicating iteration is added), it will construct an increasingly accurate representation of external reality even where there is no possibility to directly observe external reality.

A difficulty with a general theory of evolution is to understand how cognitive processes can evolve through a "constructive" process of eliminating errors that anticipate and prepare to meet future requirements, a question that Alexander Riegler (2001, 2001a, 2003) amongst others have considered at some length, as will be discussed below.

Three worlds: reality, structural and codified knowledge and "truth"

Popper (1972, 1994) considers the body-mind problem, not as a monist or dualist, but rather as a special kind of pluralist beyond Cartesian dualism (1994: p. 5, 8-9). Deriving from his understanding of the cognitive requirements to be able to criticize claims to know as objects separate from subjective cognitive processes, Popper proposed three ontological domains or "worlds", an idea first introduced in 1967 at the Third International Congress for Logic, Methodology and Philosophy of Science and published in the Proceedings (1968). These are:

World 1 *(abbreviated here as "W1")*

W1 is the world of physics and chemistry, encompassing everything that exists, i.e., this is physical reality including the uninterpreted dynamics of complex systems: "i.e., the "real world". In other words W1 is Pattee's *reality*, that is largely neglected by constructivists - not "*knowledge of reality*".

World 2 *("W2")*

W2 is the world of cybernetics and cognition that includes the embodiment of cognition and action and what Popper (1972) terms "dispositional" or "subjective" knowledge (i.e., knowledge embodied in the subject). In a physical sense, knowledge in W2 ("W2 knowledge") represents the situational propensities or dispositions embodied in the structure of a complex system that constrains the system (i.e., what I have above called "structural knowledge") to behave in certain ways in particular circumstances. In its simplest form, the cybernetic control structure of a system exhibiting feedback control is the basis for W2 knowledge (i.e., this represents Corning's "control information" - 2001, 2002). More complex forms of W2 knowledge may be represented in the structural associations and cyclical dynamics of macromolecular chemistry in a cell, or the strengthened interconnections of neurons in a brain that embody the "skills" we have learned for better interacting with the world. Polanyi's (1958, 1966) 'tacit' or 'personal' knowledge is more-or-less synonymous with Popper's W2 knowledge. W2 includes the cognitively constructed knowledge of living things as considered by constructivists. Pattee, and even more, Abel (2008, 2009, 2010), with their focus on genetic or "formal" knowledge have largely not considered the existence or nature of embodied structural knowledge. However, in Pattee's terms there is a clear epistemic cut between W1 and W2

World 3 *("W3")*

W3 is the world of the objective products of cognition, i.e., what Popper calls symbolically encoded or linguistically expressed knowledge. I disagree with Niiniluoto (1999: p. 23) who states that W3 is limited to the "products of human social action". I read Popper to say that W3 comprises the persistent *products* of all kinds of cognition. Popper clearly defined W3 to include knowledge in the objective sense, including "the world of the logical contents of books, libraries, computer memories, and suchlike" (1972: p. 74 – see also p. 115; 1994: p. 36-37) and "our theories, conjectures, guesses (and, if we like, the logical content of our genetic code)" (1972: p. 73 – see also "Long before criticism there was growth of knowledge—of knowledge incorporated in the genetic code" – p. 84), while the physical structure of the codified content remains always in W1. As linguistically expressed (W3) subjective knowledge (W2) can be consciously criticized to eliminate errors, genetically encoded knowledge (W3) is criticized by nature to eliminate carriers of errors (Popper 1994: Chapter 3 – World 3 and Emergent Evolution). W3 includes Pattee's codified knowledge and especially what Abel (2008, 2009, 2010) called "formal knowledge". A *second epistemic* cut separates the dynamic structural knowledge of W2 from the chemically relatively inert encoded objects (genetic code, writing, computerized texts) carrying W3 knowledge.

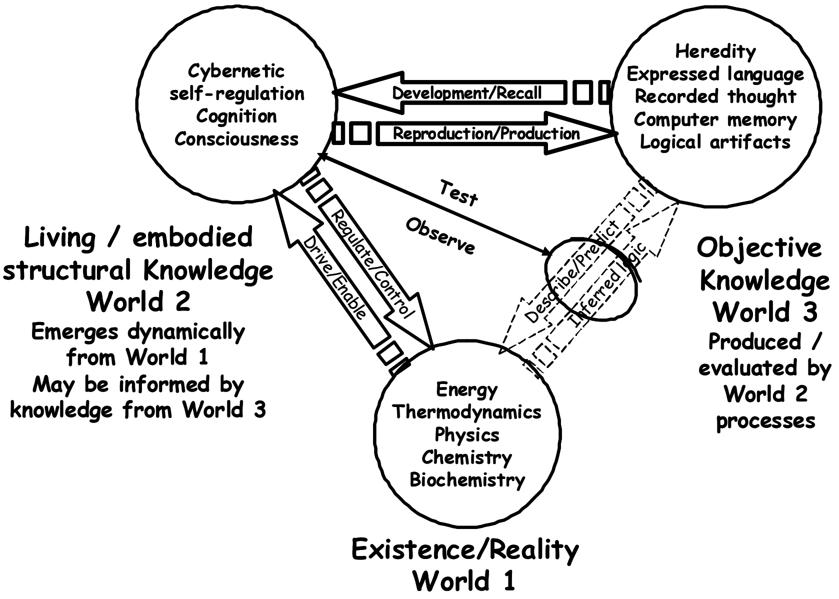


Figure 5. Interactions of Popper's three worlds (Hall 2003a).

To Popper, knowledge enters W3 and can be consciously criticized when it is linguistically articulated – a division that makes sense in literate societies. However, following Walter Ong's (1982) penetrating analysis of the use of language in *preliterate* societies, the human capacity to objectively criticize speech developed only in societies that had the concept of the *written* word. Given that speech vanishes instantaneously as it is articulated, the only surviving *impression* is not objective words, but rather what is cognitively constructed in W2 by those who heard the speech. As will be discussed below in the section on autopoietic social systems, language probably evolved originally to facilitate the coordination of (autopoietic) social systems. Only with the invention of writing did words begin to form an objectively criticizable W3.

Figure 5 illustrates the interactions of Popper's three worlds. Popper (1994: p. 7) explains the relationships of the three worlds using the example of the cybernetic control of a chemical plant. The chemical plant and its dynamics physically exists in W1, the record of temperature fluctuations (as represented by a graph created by an automatic recording instrument) exists in W3, while the dynamic cybernetic processes in W2 control the reaction rate in W1 on the basis of temperature records and knowledge of chemical reactions and plant structure persisting in W3. In the (1994) work, he stated that the automatic machines must be installed by people, and that it is only through the actions of living people (W2) that the objectives and aims existing in world W3 can be applied to the machines in W1. Popper (1972, 1994) argues that W2 emerges from W1 and W3 from W2 by evolutionary processes, but his arguments are much weaker than they could have been because he had no good definition of life such as provided by autopoiesis. These arguments will be developed in the next subsection.

Co-emergence of autopoiesis and knowledge – one cannot exist without the other

A self-defining system cannot maintain its existence without compensatory cybernetic knowledge embodied in the structured dynamic processes that maintain its functional integrity in the face of perturbations that would otherwise lead to its structural dis-integration. Corning (2001) calls the knowledge embodied in cybernetic control, "control information"; which he defines as: "The capacity (know how) to control the acquisition, disposition and utilization of matter/energy in purposive (cybernetic) processes." Corning (2002), without referencing autopoiesis or evolutionary epistemology, provides a lucid account for how this structural knowledge or control information can emerge and be shaped by natural selection to produce more complex self-producing entities. Conversely, as discussed below, autopoietic structural knowledge exists only as long as the system in which it is embodied continues to produce itself.

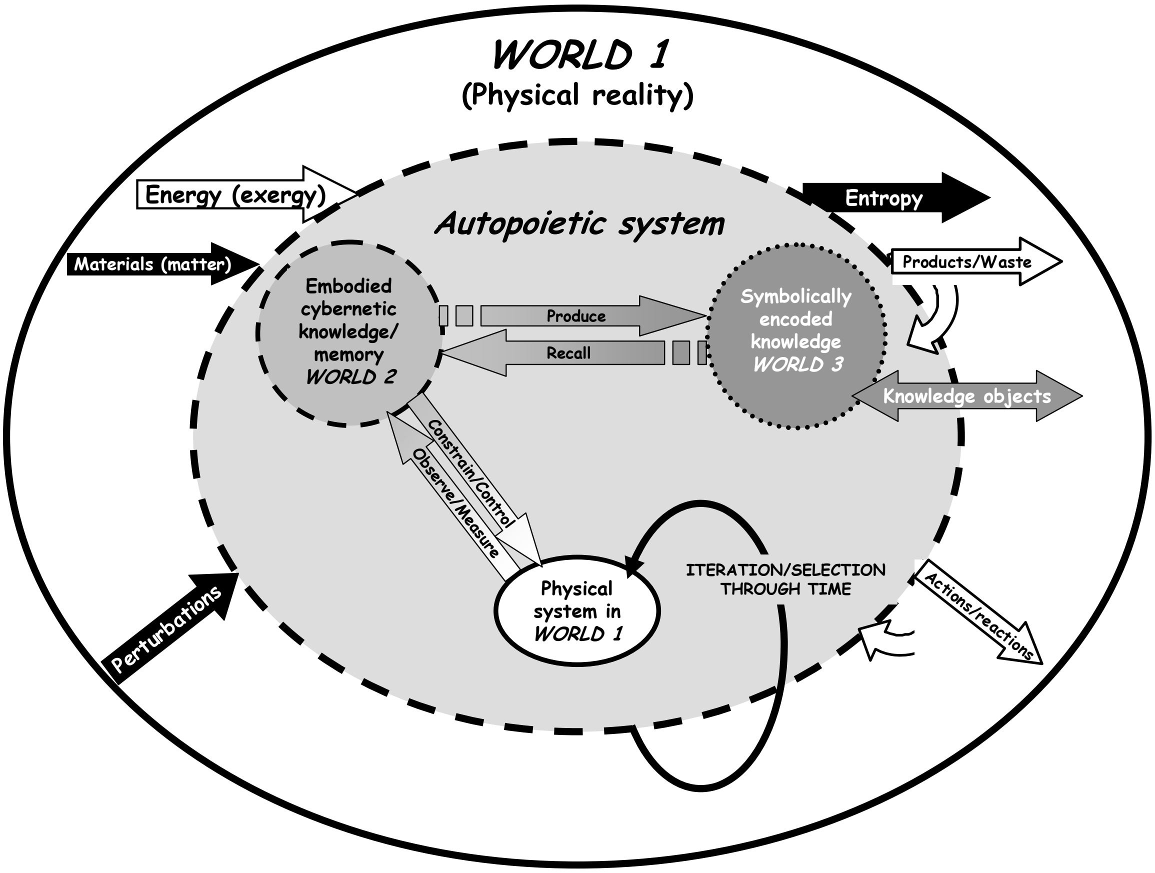
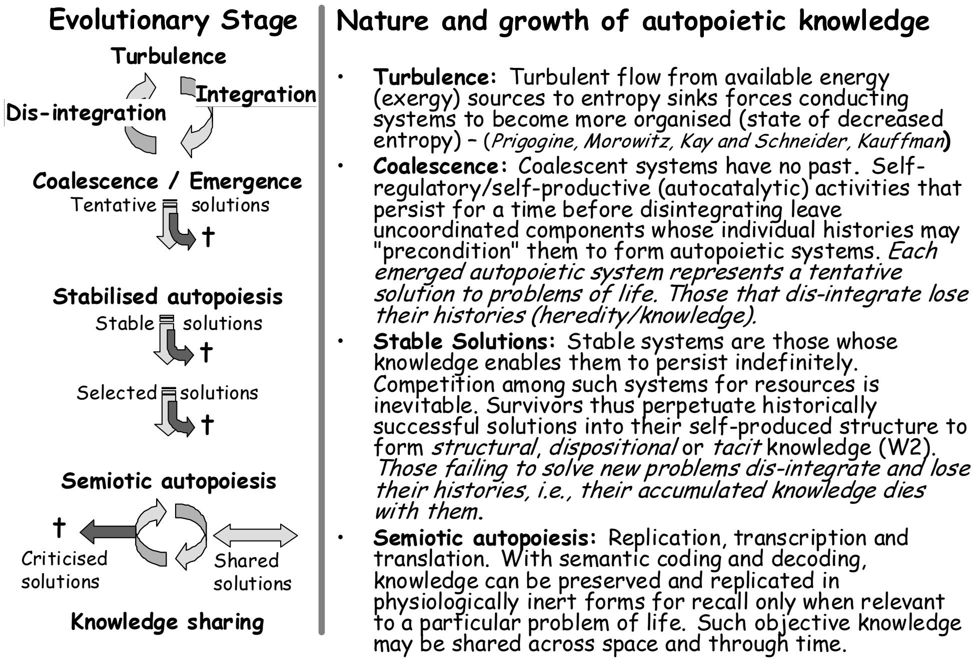


Figure 6. Three worlds in an autopoietic system (after Hall 2005)

Figure 6 places Popper's three worlds into the context of an autopoietic system. The largest oval encompasses the physical world and everything in it (W1). An autopoietic system within W1 is enclosed within the heavy dashed line that indicates its boundary with the external world. The system is permeable to energy and semi-permeable to matter. Fluxes of energy are dissipated into entropy as they pass through the system, driving production processes that convert at least some of the matter into components (products) required for the maintenance of the system's autopoiesis and exporting some of these and waste to the external world. Perturbations create "problems" that might potentially lead to system disintegration. Cybernetic feedback control processes must compensate to minimize system disturbances propagating from perturbations by acting internally or on the external world, perhaps through the production of particular products (e.g., Tsokolov 2010). Systems unable to compensate dis-integrate, and thus are selectively eliminated from the population. W2 knowledge gradually improves through processes of the generation and selective elimination of failed problem solutions. Evolution may proceed to the point where systems emerge that are able to encode knowledge into inert forms that can persist independently of living autopoietic systems, for sharing and decoding at other times and places.



Nature and growth of autopoietic knowledge

- **Turbulence:** Turbulent flow from available energy (exergy) sources to entropy sinks forces conducting systems to become more organised (state of decreased entropy) – (*Prigogine, Morowitz, Kay and Schneider, Kauffman*)
- **Coalescence:** Coalescent systems have no past. Self-regulatory/self-productive (autocatalytic) activities that persist for a time before disintegrating leave uncoordinated components whose individual histories may "precondition" them to form autopoietic systems. *Each emerged autopoietic system represents a tentative solution to problems of life. Those that dis-integrate lose their histories (heredity/knowledge).*
- **Stable Solutions:** Stable systems are those whose knowledge enables them to persist indefinitely. Competition among such systems for resources is inevitable. Survivors thus perpetuate historically successful solutions into their self-produced structure to form *structural, dispositional* or *tacit* knowledge (W2). *Those failing to solve new problems dis-integrate and lose their histories, i.e., their accumulated knowledge dies with them.*
- **Semiotic autopoiesis:** Replication, transcription and translation. With semantic coding and decoding, knowledge can be preserved and replicated in physiologically inert forms for recall only when relevant to a particular problem of life. Such objective knowledge may be shared across space and through time.

Figure 7. The emergence and stabilization of knowledge in autopoietic systems (after Hall et al. 2005; Hall 2006).

Hall et al. (2005) and Hall (2006) describe conditions under which the physical world bifurcates to form an autopoietically emerging W2 that may eventually enable the emergence of W3. This emergence can be broken into a logical sequence of several stages based on physical processes (Figure 7, Figure 8).

- *Autopoietic evolution begins with turbulence in dissipative fluxes from sources to sinks.* Complex recursive eddies or "circularly closed" vortexes in the flux of energy and materials from sources to sinks systems repeatedly form, dissipate and reform (Figure 8.a). Self-regulatory/self-productive (autocatalytic) activities close to chemical equilibrium that persist for a time before disintegrating may produce components whose origins in self-producing systems "precondition" them to participate in the formation of other autocatalytic systems. Newly coalescent autocatalytic systems have no past, but if an emergent eddy has any autocatalytic/autopoietic capacity for self-production, while it survives it will produce more components of kinds that have the tested capacity to participate in the formation of such systems. Each emerged autopoietic system represents tentative solutions to problems of life. Those that dis-integrate lose their histories (heredity/knowledge). However, it can be assumed that components multiplied and tested in such temporarily autocatalytic/ autopoietic systems will survive for a time and become more common in the environment, and thus increase the probability that more autopoietic eddies will form based on these tested components. In other words, at least in this very early stage, autopoiesis increases the fitness of the environment to support autopoiesis.

- *Stabilized autopoietic systems* are those complex entities whose tentative solutions embodied in self-regulatory feedback enable them to persist indefinitely in the face of at least some system disturbances, thereby establishing lineages through historic time (Figure 8.b). At this stage survival knowledge is embodied in the fitness of the component subsystems and their networking to participate in self-regulation and self-production of processes within the entity. Those entities that fail to solve new problems dis-integrate and lose the historical successes of their embodied solutions. Successfully stabilized autopoietic systems may grow to the point where physical perturbations such as turbulent shearing cause fragmentation. If the network of processes producing autopoiesis are distributed, fragments may retain enough components of the necessary processes to continue autopoiesis – thus multiplying the number of entities sharing "inherited" knowledge that survives fragmentation (Maturana and Varela 1973; Varela et al. 1974). Morowitz (1999), Morowitz & Smith (2007), Rasmussen et al. (2003), Pross (2005, 2009), and Khodorkovsky (2004) provide examples of what this phenomenon may look like at the chemical level. This type of knowledge transmission is called "compositional inheritance" Segre et al. 2000a, 2001; Wu & Higgs 2008).

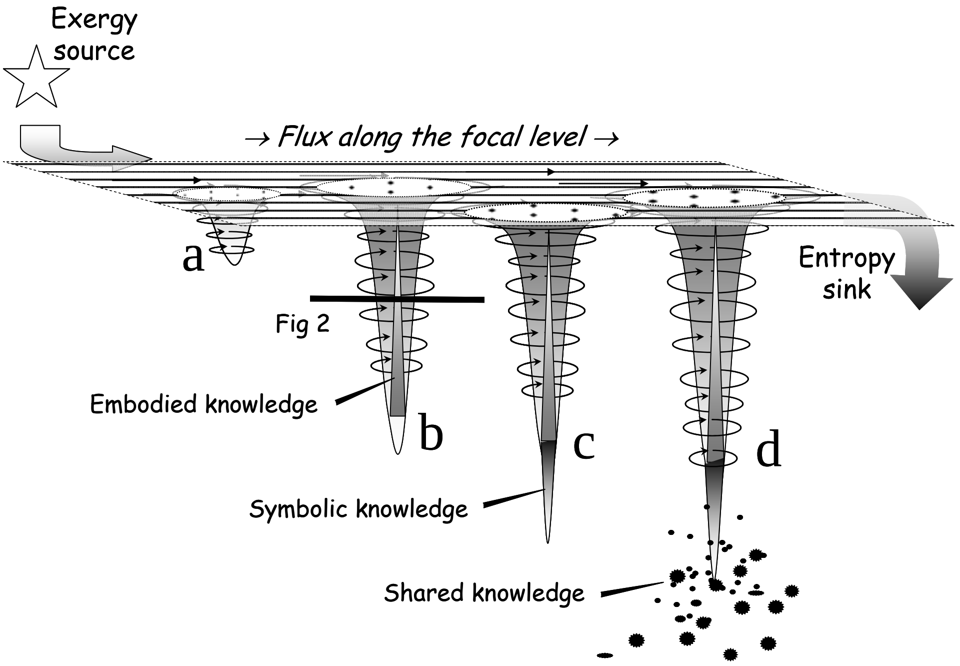


Figure 8. Stages in the emergence of autopoietic knowledge in turbulent fluxes of energy from sources to sinks (after Hall et al., 2005; Hall 2006). The metaphor is the dissipation of potential energy in the formation of eddies along the surface of a stream of water flowing from a higher elevation to a lower one. The ultimate source is high potential solar radiation or geochemical sources, while the ultimate sink for both is the radiation of entropic heat to the 3° K night sky (Morowitz 1968; Morowitz 1999; Morowitz & Smith 2007). (**a**) the initial "coalescence" of autopoietic cycles in a turbulent flow of matter dissipating energy as it is transported from a source to a sink (Figure 7); (**b**) "stable solutions" where embodied structural knowledge (W2) stabilizes autopoietic systems against dis-integration. (**c**) an early stage in the construction of symbolic knowledge (W3). (**d**) "semiotic" autopoiesis where persistent objects containing symbolic knowledge are able to be exchanged between autopoietic entities. Figure 1 illustrates a cross-section of the developing entity at stage b.

- *Dispositional autopoiesis* (also Figure 8b) refers to the state where autopoietic lineages perpetuate historically successful solutions for survival into their self-produced processes and material structure as tested compositional inheritance (i.e., structural or dispositional knowledge - W2) . Where self reproduction becomes common, competition is inevitable for limiting environmental resources of exergy and material components required for self-production, growth and replication such that lineages begin to be starved for energy and resources and disintegrate. The consequence of error elimination is that survival knowledge will grow in those lineages that best survive their problems of life.

- *Semiotic autopoiesis* (Figure 8c) evolves when lineages evolve means to preserve their tested survival solutions in comparatively inert persistent forms able to be retrieved when relevant to particular problems of life (W3), as discussed in more detail below. Semantic encoding creates an epistemic cut between system dynamics and energetically degenerate media for storage and replication. DNA-based genetic and developmental systems involving replication, transcription and translation are one kind of coding solution. Linguistically encoded memory is another such solution. Where knowledge objects can be expressed linguistically, they are able to be consciously criticized to eliminate errors without the need to embody the knowledge in entities that are eliminated if their enacted solutions are erroneous.
- Knowledge sharing across space and time (Figure 8d) is enabled when knowledge is codified in "objective" W3 forms able to persist independent from knowing entities able to decode the knowledge objects. Bacterial transformation, transduction and conjugation (Hurlbert 1999; Mulligan 1997-2005), and sexual recombination in eukaryotic cells represent such knowledge transfer and sharing. Where linguistically expressed objects are shared, they can be intersubjectively criticized.

To this point I have implied that Popper’s three worlds are something more than metaphysical constructs, i.e., that they actually have an existential meaning in the physical dynamics of reality. This will be explored in more detail in the next section.

COGNITION, CODIFIED KNOWLEDGE AND SYSTEMS OF HEREDITY

Assuming that the structure of the coalescent system and its medium provide the possibilities, even though there is no mechanism to objectively codify and store control information, natural selection will begin to build survival 'knowledge' whenever/wherever self-producing systems persist long enough to begin accumulating a connected history as compositional inheritance. In the framework of Popper's 'general theory of evolution', it is a truism that those systems that disintegrate and return their components to the blind chaos of W1 do not build knowledge. However, where systems have by chance ("blind variation") coalesced into a structure that includes some homeostatic capacity that allows them to maintain their historical integrity in the face of perturbations, this structure then embodies some W2 survival knowledge. Note that the concept of embodiment of knowledge in an entity implies that it is diffusely present in the overall structural organization of the entity and not necessarily present as 'control information' in a discretely codified or even codifiable form.

Structural heritage

Even if partially autocatalytic systems later disintegrate to return their components to the environment, systems that successfully produce more of the same kinds of components that are involved in their structure will make it easier for other autocatalytic systems using those components to emerge from that environment. This might be considered a form of environmental knowledge (where knowledge is defined as ‘solutions to the problems of life’). The stage between Turbulence and Coalescence in Figure 7 illustrates this stage.

Thus, even the survival over limited time of homeostatic systems having some autocatalytic capability to produce suitable components may work to prepare the environmental medium to more readily form such systems. It is reasonable to believe that in this epoch, the W1 environment will be changed in directions that shift the equilibrium between integration and dis-integration of components so that self-productive systems form more frequently and do not so readily fall apart. It follows that coalescent entities with favorable structures will 'live' for increasingly long stretches of time, until lineages are formed that do not readily dis-integrate. These surviving lineages establish continuous historical heritages. Survival knowledge continues to accumulate in a lineage as long as the lineage survives in an organized state with an unbroken history (i.e., heritage). In Figure 7, this is ‘stabilized autopoiesis’.

To now reproduction has not been considered. However, with historical continuity, 're-production' begins to play a role. In its simplest form (i.e., requiring the least knowledge beyond the state of flux close to equilibrium), reproduction would probably involve nothing more than incorporating additional components in favorable ratios and structural locations to grow larger until the assemblage becomes physically unstable and fragments into pieces. If at least some of the fragments retained enough of the favorable structural organization to maintain an autopoietic existence, those histories would be preserved and added to. Even this nearly chaotic form of replication would serve to multiply the history of solutions that worked. It becomes quite appropriate then to talk about the currently surviving entities as 'spearheads' (Popper 1972:243) inheriting dispositional knowledge embodying in their structures solutions to the problems of life (i.e., 'survival knowledge' or control information) replicated from their linear ancestors.

Obviously with no genetic system to retain and reproduce control information in any objective form, the propagation of survival knowledge would be subject to chaotic variation and it is likely that fragmentation would perturb many incipient lineages to the extent that they dis-integrate and lose their accumulated history. However, as long as some lineages survive, those that do survive will continue accumulate more and more survival knowledge (Popper’s general theory of natural selection and Campbell's blind variation and selective retention). Also, in the early days of this process when autopoietic systems do not survive for long, disintegrating systems will return their once functional components to the medium, thus maintaining or even improving favorable conditions for the coalescence, emergence and growth of other autopoietic systems.

However, when systems with longer and more successful histories and re-productive abilities begin to accumulate in the environment, the more successful survivors will compete for and sequester suitable ready-made functional components and consume easily available exergy resources to fuel their continued growth and multiplication. This will eventually destroy the close to equilibrium situation that made the initial emergence of autopoiesis possible. This creates selection to use available resources of components and exergy more efficiently, and to modify or synthesize required components from simpler/lower value starting materials. Eventually, environmental conditions will no longer favor the coalescence of new lineages and the survivors will thus move farther away from equilibrium. In Figure 7, this represents the stage of dispositional autopoiesis – referring to Popper’s (1972) concept of W2 knowledge embodied in the structural "disposition" of organisms. This is called “compositional inheritance” (Segre & Lancet 2000; Segre et al. 2000, 2001a; Wu & Higgs 2008) or “live memory” (Bentolila 2005).

It follows from this that autopoietic entities are “*evolutionary* [or Darwinian] *individuals*”. Janzen (1977) defined the term to designate the individual entity that natural selection operated on (i.e., whose death or failure to reproduce) prevented transmission of its hereditary knowledge to subsequent generations. Gould (2002: pp. 608-613) listed the properties that qualified an entity to be considered to be an evolutionary individual:

- *Reproduction* – the evolutionary individual must have the capacity to produce progeny.

- Inheritance – progeny must on the average inherit information/knowledge from their specific parent(s) that on average makes them more like their parent(s) than are the progeny of other parents in the population.
- Variation – progeny of given parent(s) must show some degree of heritable variation from one another.
- Interaction – for entities at any level of organization to be considered evolutionary entities, they "must interact with the environment [and other individuals] in such a way that some individuals achieve greater reproductive success as a causal result of heritable properties manifested by these [individuals]…, and not manifested (or as effectively expressed) by … [other] individuals." (Gould 2002: p. 611)

This accords well with Popper's (1966 [1972: pp. 241-244]) "general theory of evolution". Once there are autopoietic entities with sufficiently reliable re-production of their compositional inheritance, these can be considered to be evolutionary individuals.

Codification to preserve knowledge in W3

To this point, I have discussed the origins of autopoiesis only in the most general terms. However, laboratory work suggests that simple and perhaps even complex organic polymers will form in the prebiotic chemistry of an aqueous reducing environment containing compounds based on C, H, O, N, P, S, etc. that subjected to almost any kind of excitation energy sufficient to activate simple carbon based molecules to the point that they can relax by bonding with other molecules, or heat flux situations that favor polymerization through dehydration reactions:

- *Protein world*: Amino acids polymerize into protenoids that can form micelles when rehydrated. Some randomly formed proteinoids have shown at least mild catalytic activity and excitability (Fox 1980, 1991, Fox et al. 1994; Andras & Andras 2005; Pollack et al. 2009).
- *Lipid world*: Lipids can group together form bilayered vesicles, where hydrophilic radicals face either the interior space of the vesicle or the environment (Cavalier-Smith 2001; Segré & Lancet 2000; Segré et al. 2001; Sharov 2009; Mulkidjanian et al. 2009).
- *RNA world*: Nucleotides with energy rich phosphate groups can transfer activation energy held in the phosphate group to other molecules in ways that may activate them to polymerize; or, through loss of active phosphate groups or even simple physical dehydration (e.g., Smith et al. 1967, Kazakov et al. 2006) they can polymerize themselves or form ribozymes to help assemble long nucleic acid polymers (Woese 1967; Crick 1968; Orgle 1968, 2004; Hughes et al. 2004; Muller 2006; Wu & Higgs 2009; Briones et al. 2009).
- *Metabolic world*: Morowitz (1999), Morowitz & Smith (2007), Smith & Morowitz (2004), and Srinivasan & Morowitz (2009) argue that intermediary metabolism based on small molecules driven by redox/electrical potential differences probably evolved first, as summarized by Trefil et al (2009).

Arguably none of these "worlds" may have much evolutionary potential on their own, but a mixture of the various polymers, monomers and substrate materials, when subjected to the organizing forces of a thermal or ionic flux from source to sink, may lead to coalescence where conditions are particularly favorable to form incipiently autopoietic organizations (e.g., Martin et al. 2008; Pollack et al. 2009).

One of the problems on life in lineages whose only form of historical knowledge is compositional inheritance embodied in the three dimensional dynamics of their structure, is to retain through time their successful solutions with some degree of fidelity, especially through the process of reproductive fragmentation (Bentolila 2005; Vasas et al. 2010). Based on the arguments above, I am not so pessimistic as Vasas et al. that substantial evolution of non-genetic memory in what they called "ensemble replicators" cannot occur in the absence of a formal (W3) genome. Although individual coalescent autocatalytic systems (i.e., an organized autocatalytic set – Kauffman 1983) many not survive for long, assuming that such coalescent autocatalysis emerges in a local environment close to an equilibrium between disorganized components and components with an autocatalytic organization, what Vasas et al. neglect is that autopoietically functional components are multiplied while autopoiesis lasts. These will be released to the local environment on dis-organization to potentially move the equilibrium towards more sustained autocatalysis resulting in genuine evolutionary lineages. Nevertheless, any system capabilities that serve to protect aspects of proven solutions by codification and packaging would have selective value by comparison to the chaotic reproduction of diffuse structural knowledge through passive fragmentation.

Based on evidence for heterocatalytic (i.e., enzymatic ribozymes) as well as potentially self-replicating properties of nucleic acid polymers, it is reasonable to suppose these macromolecules may have played cybernetic control functions in the proteinoid-based metabolism early autopoietic systems. This would facilitate the evolution of a system of "codified" control information by establishing an epistemic cut between the dynamic structural knowledge of the reproducing entity and persistently encoded control information. By taking advantage of the autocatalytic polymerization and replication capabilities of the nucleic acid polymers, an autopoietic system replicating these molecules, would *also* be replicating any structural or enzymatic functions of those molecules performed in the autopoietic system (Hughes et al. 2004). In today's systems DNA appears to have no direct roles in active functions. RNAs still serve both as code carriers (in transfer RNA) and structural/catalytic roles (in protein synthesis).

Once any structural knowledge or control information relating to the autopoietic system as a whole is able to be represented in the structures of macromolecules that are themselves autocatalytic, the self-preservative capacity of autocatalysis can be shaped and improved through further stabilization of lineages carrying such macromolecules. This represents the first population of Popper's W3 with persistent and potentially shareable survival knowledge (Fry 2010; Dennis et al. 2009). The value of protecting the tested knowledge in such stable and self-replicating molecules sets the stage for evolution of the kinds of DNA and RNA-based epistemic systems we now know as genetic systems. Pattee (1982, 1995, 1995a, 1997, 2001, 2001a, 2006, 2007, 2008, 2009) has discussed at length stages in the refinement of replication, transcription and translation systems for the semiotic preservation and application of knowledge (without understanding the earlier role of ensemble replication in the inheritance of control information).

In this discussion it should be noted that supposed evolutionary path to codified knowledge offers no means to translate *embodied experience* of life *into DNA code*. There is no evidence that such a system exists even today. The closest is to control the transformation and translation of parts of the code via epigenetically heritable methylation (Jablonka and Lamb 1998, 2006; Surani 2001). As discussed by Kauffman (1983), knowledge of life has been built into DNA codes solely through the process of blind variation and death of lineages carrying code variants that disrupted or reduced survival of those lineages. As Popper argued quite effectively, what is left will in general encode a broader, deeper and overall more effective response to the problems of persisting in the real world. Thus, the nucleic acid codes based on 3-base codons to specify a single amino acid is purely a product of natural selection operating over billions of generations of autopoietic replication, and not one of rational design.

Knowledge sharing and sex

In today's epoch, all living entities maintain codified (W3) knowledge for survival in sequences of nucleotide monomers forming nucleic acid polymers called chromosomes. As Kauffman (1993) discusses at some length, although the blind introduction of new control information can further stabilize, change or even add new attractor basins for the autopoietic system, more frequently new information will perturb the organizational dynamics of the system out of an autopoietically perpetuated attractor basin onto a dynamic trajectory that leads to chaos and disintegration (see also Vogan & Higgs 2011). There will be obvious advantages to lineages possessing means to isolate code sequences tested through survival in the lineage from exogenous codes by maintaining these codes behind barriers that keep out foreign codes and/or to evolve systems that degrade DNA strands taken up from the environment before any codes they carry are translated or recombined with inherited chromosomes. Both strategies are well known in living organisms today.

Once barriers evolve to cut off the existing survivors of an embodied lineage from the promiscuous exchange of codified control information, different kinds of trophic specialization can begin to evolve as distinct *clonal species*. Hall (1966) discusses some likely circumstances and selection pressures leading to the differentiation prokaryotic and eukaryotic organisms as distinct types of trophic specialization emerge from the era when life was physically or genetically promiscuous[6].

However, there is a downside to genetic isolation. Isolated individuals of a clone no longer have access to share in a wide range of experientially tested knowledge from other, related individuals, and evolution of the isolated lineage is limited to the slow pace of change in single lineages. Thus, it is likely that strategies would evolve to allow the continued exchange of genetic information between closely related lineages (i.e., those sharing many genes in common due to a comparatively recent common ancestry, and thus unlikely to be disrupted by exogenous control information).

Early life must have still been quite fragile by comparison to the kinds of robustly self-maintaining cellular organisms we know today. Dis-integration would have been a common phenomenon, scattering workable components into the environment - including usefully coded nucleic acid sequences that would then be available for incorporation into other living entities. Even today many bacteria retain the capacity to share and incorporate “raw” exogenous codes into their functional genomes by processes of “*transformation*” (Avery et al. 1944). Thus, I would argue that at least in the early stages of the evolution of life after the emergence of a codification system, all living things shared a common pool of hereditary knowledge, more or less in every possible combination (Hall 2006). In Figure 7, this represents the stage of semiotic autopoiesis. Through this point in the evolution of life, it is very likely that survival knowledge is shared promiscuously via fissions and fusions and disintegration and coalescence of autopoietic patches in the overall dissipative media.

One strategy for identifying whether an exogenous piece of naked chromosome taken up from the environment might be useful is to test whether it has a sequence of code matching that in the host cell (i.e., because it came originally from a related individual. In this case, some or all of the exogenous DNA may be spliced into the cell's chromosome, replacing the more or less matching existing segment (note: this DNA splicing still forms the basis for all genetic recombination today, including the swapping of chromosome

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[6] There are important differences between Hall's approach and Margulies's (Sagan 1967; Margulies 1968, 1970).

segments that takes place in eukaryote meiosis). A second, more sophisticated strategy, would be to package or wrap chromosomal control information in the same kind of material that members of the clone use to bound their autopoietic spaces from the external environment. Presumably this genetic package would then be recognized as belonging to a self sharing a common ancestry, and thus be safe to assimilate. However, given that selection can operate at many different levels of organization (Gould 2002; Wilson & Wilson 2007; Durand & Michod 2010), in some cases the packaged codes have evolved to replicate themselves as bacteriophages or viruses at the expense of the cells that absorb them. Where functional bacterial genes are transferred without killing the recipient cells, this virally mediated process is known as *transduction* (Zinder and Lederberg 1952). *Conjugation* is a still more sophisticated process involving physical contact (thus allowing the recipient to "assess" the genetic donor as being "conspecific") was discovered by Lederberg & Tatum (1947). Eukaryote sex involving meiotic cell fusion, genetic recombination and assortment will be discussed briefly in the next major section.

However, it is likely that some combinations of genes would work better together to stabilize and grow in some autopoietic patches than would other combinations in other patches. There would be advantages to lineages possessing such combinations if the different genes were physically linked together in self-reproducing packages (i.e., Chromosomes encoding compatible bits of control information in its genes).

Two worlds of organismic knowledge or "code duality"

Hoffmeyer and Emmeche (1991), Emmeche & Hoffmeyer (1991), Hoffmeyer (2000), and Hoffmeyer (2002a) as discussed in detail in Hall (2006) have also considered the evolutionary origins of the self-referential capability to apply control information as required for autopoiesis and life. They present an evolutionary epistemology based on what they call "*code duality*" that is similar to Popper's, where they consider compositionally inherited structural knowledge to be an "analog" code (W2) and the knowledge that is genetically encoded in nucleic acid polymers to be "digital" code (W3). Following Pattee, they recognize the existence of two epistemic cuts, the first between the world and the analog "code", and the second between the analog and digital codes.

Hoffmeyer (2000: pp. 179-180) gives three important characteristics of the digital DNA code that makes it indispensable for evolutionary processes today (also highlighted by Pattee, but not so succinctly):

- *Freedom from the constraints of nature* (any sequence of nucleotides is possible – i.e. because there is no strict binding between the code itself and the message it carries when it is translated).
- *Objectivity and temporality* (i.e., the code can persist through time in its objective format independently from its living source. The code "is actually protected from the vicissitudes of life by its relative chemical inertness", a point also particularly emphasized by Pattee).
- *Abstraction* (i.e., the separation of the code from its message allows the expression of metamessages "necessary for the interpretation of other messages", as in the higher level semantic control of development).

These are, of course, the characteristics for W2 as I have defined it earlier (Popper's inclusion of articulated speech in W3 blurs the criterion of objectivity and temporality. Hoffmeyer (2000) calls W2 knowledge, "tacit cellular knowledge", but does not so succinctly characterize it. For W2, I would give the following characteristics:

- *Constrained by history and dynamical laws* (compositional heritage is propagated from one instant to the next by the causal dynamics determining the adjacent possible of the next instant from the instantaneous now. The actual present may be constrained by causal dynamics propagating from the translation of W3 codes into the structure of the instantaneous now).
- *Immediacy and subjectivity* (what is propagated to the next instant depends solely on the physical configuration of state space in the immediately prior instant, and this is unique for each individual subject. Although the present configuration of state space is causally determined by its past, only the present determines the next future state).
- *Concreteness* (although a history of problem solutions is embodied in the instantaneous structure of phase space and may have the effect of anticipating future requirements, these are applied only in the present instant by determining what is possible in the next instant.)

THEORY OF HIERARCHICALLY COMPLEX SYSTEMS AND THE EMERGENCE OF HIGHER ORDERS OF AUTOPOIESIS

Foundations

The modern theory of hierarchically complex systems was established by the Nobel laureate, Herbert Simon (1962, 1973, 2002; Simon & Ando 1961) and has been substantially elaborated from biological points of view by James Grier Miller (1978) and Stanley Salthe (1985, 1993 – who in 1985 makes only the slightest references to Miller's work and none in 1993). "[A] *hierarchic system*… [is] composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure until we reach some lowest level of elementary subsystem" ([my italics] Simon 1962: p. 468). Even at the macromolecular/ cellular level of structural evolution it is likely that early autopoietic systems showed some level of hierarchically modular organization that may have affected the ease with which autopoiesis evolved.

Complicated/complex systems can be assembled and evolve faster in response to external conditions if they are modular. Simon (1962), demonstrates this using the parable of the watchmakers Hora and Tempus as an example. Both assemble watches containing on the order of 1,000 parts each. Hora's watch was assembled piece by piece, and disintegrated if the work was interrupted. Tempus assembled his parts into stabile low level modules of about 10 parts each, that were in turn assembled into higher level subassemblies that were also stabile, each containing about 10 modules from which the watch as a whole was assembled. If this assembly process was interrupted at any point, only a small amount of work would be lost. Simon shows that if the probability of either watchmaker being interrupted while adding a single part is .01, it will take Hora approximately 4,000 times as long to complete a watch as it does Tempus. Hora fails in business, while Tempus is very successful, something that has very clear implications for the evolution of biological systems – a point Simon makes immediately:

> The time required for the evolution of a complex form from simple elements depends critically on the numbers and distribution of potential intermediate stable forms. In particular, if there exists a hierarchy of potential stable "subassemblies," with about the same span, *s*, at each level of the hierarchy, then the time required for a subassembly can be expected to be about the same at each level-that is proportional to $1/(1-p)^s$. The time required for the assembly of a system of n elements will be proportional to $\log_s n$, that is, to the number of levels in the system. One would say—with more illustrative than literal intent—that the time required for the evolution of multi-celled organisms from single-celled organisms might be of the same order of

> magnitude as the time required for the evolution of single-celled organisms from macromolecules. The same argument could be applied to the evolution of proteins from amino acids, of molecules from atoms, of atoms from elementary particles. ...
>
> The effect of the existence of stable intermediate forms exercises a powerful effect on the evolution of complex forms that may be likened to the dramatic effect of catalysts upon reaction rates and steady state distribution of reaction products in open systems. (1962: pp. 471-472).

Simon goes on to argue that this process is not teleological, direction is provided purely by natural selection favoring more stable components over less stable ones, and that hierarchically complex systems will be able to evolve much more rapidly than systems with "flatter" structures (Simon 1962, 2002).

Simon's analysis of hierarchically complex systems is based on the concept of "near decomposability" of composite systems, as defined by Simon & Ando (1961) and Simon (1962)[7], near decomposability concentrated mainly on the "vertical" structure of the complex system:

> [C]omposite systems, [are] constructed by the superposition of: (1) terms representing interactions of the variables within each subsystem; and (2) terms representing interactions among the sub- systems. …[O]ver a relatively short period, the first group of terms dominates the behavior of the system, and hence each subsystem can be studied (approximately) independently of other subsystems. Over a relatively long period of time, on the other hand, the second group of terms dominates the behavior of the system, and the whole system moves, keeping the state of equilibrium within each subsystem-i.e., the variables within each subsystem move roughly proportionately. Hence, the variables within each subsystem can be aggregated into indexes representing the subsystem. Thus, the system of variables in the case just described can be represented as a two-level hierarchy, with the aggregative variables at the higher level [and] there is no reason why we need to restrict ourselves to a two-level hierarchy. (Simon & Ando 1961: p. 132)

In other words, even though sub-systems are themselves complex entities, because their internal activities resolve so rapidly by comparison to the higher level system they compose, the details of these internal interactions can be largely ignored by comparison to the interactions of subsystems with one another within the system (i.e., from the higher level view, subsystems interact with one-another in law-like ways as simple entities or 'particles'). Looking at what this means in another way, the system has an identity is essentially independent of the individual identities of the subsystems that compose it.

Simon (1973) focused on the "horizontal" interactions of components at a level of organization and noted that subsystems could be discriminated by the fact that the internal components of a subsystem interact much more frequently/rapidly with one another than they do with components of other subsystems at the same level – i.e., they exhibit "loose horizontal coupling" (Simon 1973: p. 15 et seq.) and where a system may be composed of a comparatively small variety of subsystems, where each variety is represented by many functionally equivalent subsystems (e.g., human bodies are built from only a few hundred different kinds of living cells). Simon suggests that adaptive evolutionary changes may take place independently in any one of these without requiring changes to other subsystems.

Focusing on holons

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[7] See also Maturana's (1980) usage of the term composite.

Simon's (1962) theory showed how in analyzing organizations and living entities it was easy to distinguish wholes and parts. However, Arthur Koestler (1967, 1978) noted that an entity in such a hierarchy acts as a self-contained whole to its component parts, but at the same time is a dependent component of a higher level entity, such that an entity can never be completely isolated from its network of hierarchical relationships. Koestler introduced the term "*holon*" for a component in a hierarchical system, and described it in terms of the "Janus" effect after the two-faced god, with one face always turned towards the higher level "master" system in which the holon is a component, and the other face always turned towards the lower level "subordinate" systems, i.e., a holon is a system that is at the same time a part in a higher level whole, and a whole for lower level parts. A "*holarchy*" as a hierarchy of holons functioning (a) as semi-autonomous wholes controlling their parts, (b) as dependent parts controlled by a higher level, and (c) in co-ordination with their local environment. As will be seen, qualification (c) confuses the issue.

Stanley Salthe (1985, 1993) further extended Simon and Koestler's ideas from subatomic particles to the Universe, and introduced the particularly useful idea of the "*focal level*" (Figure 9): "That level of a hierarchical system which is being examined or considered by an outside observer" (Salthe 1985: p. 290). Salthe considered that for holonic systems that change through time, most upward or downward causes could mapped from the next higher level system (acting as an environment) or from the next lower level systems that determine what is possible for the holon to do.

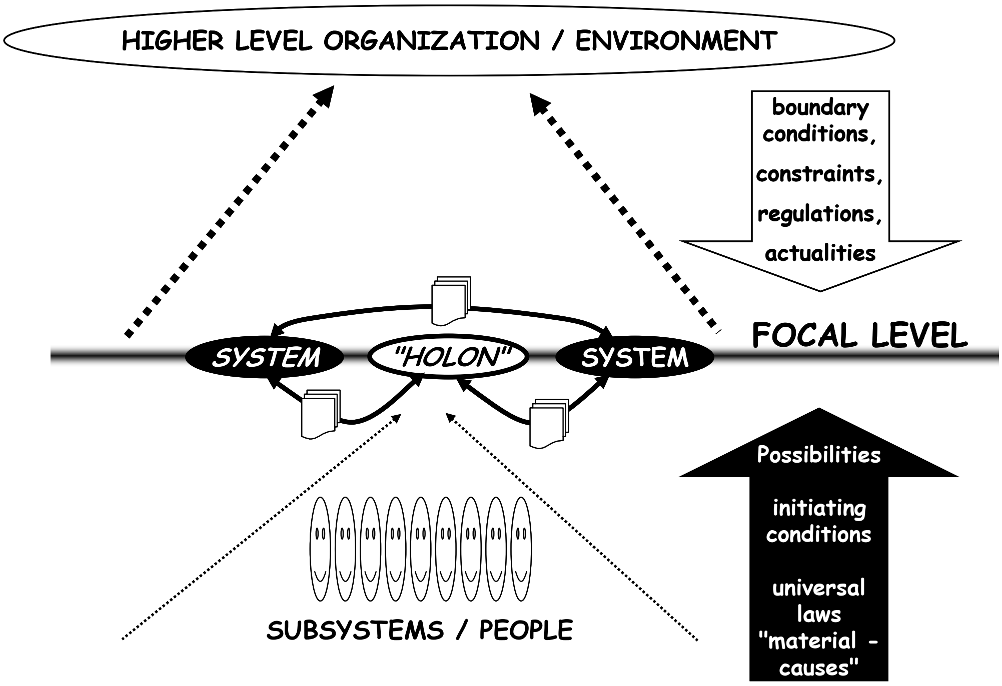

Figure 9. The focal level in the structure of a holonic or triadic system – in this case within a social system (after Hall et al. 2005). The arrows labeled by the "documents" icon represent exchanges of knowledge via W3.

Other views of the complex hierarchy of living systems

Two other workers have made important and relevant contributions to the theory of hierarchically complex living systems – especially with regard to social systems: James Grier Miller, with his "living systems" theory and Stafford Beer, with his "viable systems model". Schwaninger (2006) and Nechansky (2010) review and compare the two models. Schwaninger notes that until his analysis, there had been little cross-referencing between the two authors' schools. Beyond, this, I have found virtually no cross references between them and organsmic biologists, or those concerned with autopoiesis or constructivism. It would be beyond the scope of this paper to do more than briefly summarize their main ideas.

Miller, trained as a psychologist, began his major writing on hierarchically complex living systems in (1955). This was followed up in (1971) by a major paper in Currents of Modern Biology covering cells, organs and organisms, and beginning in 1971 by a series of papers in the journal Behavioral Science covering groups, organizations, society and supranational systems; a massive book (1978), and again in a brief summary with his wife (1990) under the conceptual title "Living Systems". Miller's intellectual sources at this time were in the cybernetics camp: von Foerster, Bertalanffy, Ashby, von Neumann and Shannon. In (1978) the ideas were all collected together and expanded incorporating Simon's ideas regarding hierarchically complex systems in the book Living Systems (1978). Miller focuses on 7 levels of "living" organization: cells, organs, organisms, groups, organizations, societies and supranational systems; and recognizes 19 (or 20 in Miller & Miller 1990) critical sub-systems necessary for viability that can be identified at each of the 7 levels. These are divided into systems that process both matter-energy and information (i.e., "reproducer" and "boundary"), those that process matter-energy only, and those that process information only. Miller 1978: p. 18 defines living systems as those that have the following properties, either within the system itself or that it has parasitized or "borrowed" from a host or symbiotic system. The boundary subsystem is particularly important in defining a living system:

- Open to matter and energy,
- Maintain a relative state of negentropy by taking in high energy foods and fuels and excreting lower energy waste,
- More than a certain minimum degree of complexity
- Largely composed of an aqueous suspension of macromolecules
- They have a "decider" (i.e., a system controlling the way subsystems and components interact
- They have certain critical subsystems or have a parasitic or symbiotic relationship with other systems that provide the functions of these subsystems
- Their subsystems are integrated together to form actively self-regulating, developing, unitary systems with purposes and goals (cf. definition of autopoiesis)
- They can exist only in a suitable environment that satisfies their needs.

By contrast to Miller's background in psychiatry, Stafford Beer was primarily a cybernetician and a founder of the Operations Research Society, primarily interested in management control systems. He knew Humberto Maturana when he was designing control systems for the Chilean national government under Salvador Allende, and wrote the Preface to Maturana & Varela (1973) – Beer (1973). Beer (1981) and Medina (2006) detail the history of Chilean involvement, that might be called a grand failure of Beer's attempt to actualize his ideas at a national level.

According to Beer (1979, 1981, 1984, 1985), there are five necessary and sufficient interactive subsystems that must be involved in a person or asocial system at any level of organization involving people for it to be considered to be viable:

- *System 1* – the operating units or elements required to "produce" the organization ("i.e., the system's autopoietic generators, to use Maturana's terminology".

- *System 2* – the self-regulatory apparatus amplifying lower level regulation, attenuating dynamic oscillations, and coordinating activities of operating units via information and communication.
- *System 3* – the guidance apparatus providing synergies, allocating resources and optimizing performance of the operating elements. Also includes an audit function to investigate and validate information flows between the operating units and systems 2 and 3.
- *System 4* – the planning and innovation function.
- *System 5* – the goals and values setting function.

Beer also claimed that viable systems must be "recursive", such "that every viable system contains and is contained in a viable system" (Beer 1984: p. 8) to form hierarchical organizations of several layers down to the individual humans comprising them. However, despite Beer's connections with Maturana, his system seems to me to be excessively theoretical and lacks connections with the real world. Where he was given more-or-less free rein to build a national system in Chile, he was catastrophically defeated by people's natural tendencies to resist central planning and central planners' limits to rationality (Simon 1947, 1955, 1979; Else, 2004; Hall et al., 2007, 2009, 2010, 2011).

Simon, Salthe and Miller all assume that the living system is perceived and discriminated by an observer. Miller recognizes the importance of boundaries in system self-maintenance.

Some focal levels, e.g., macromolecules, organs, organ systems, are distinguished by an observer for his/her own convenience. Others, e.g., living cells, and as I will argue below, multicellular organisms, human organizations, etc., are self-distinguished by the autopoiesis and interactions of living entities on that level of organization.

AUTOPOIETIC SOCIAL SYSTEMS

Maturana and Varela (e.g., Maturana 2002: pp. 13-14) eventually concluded:

> Autopoiesis happens spontaneously when the molecular dynamic conditions that can give rise to it occur in a process that takes place without external or internal guidance. …[Thus] autopoietic systems [can] exist only in the molecular domain, because the molecular domain is the only domain in which the interactions between the elements that compose it produce elements of the same kind as a spontaneous result of their structural dynamics.

The theory of hierarchically complex systems as reviewed above (e.g., based on Simon, Salthe and including the kinds of structured subsystems described by Miller and Beer) demonstrates that dynamical systems can be readily discriminated as individuals at many hierarchical levels of structural organization. Where dynamical individuals at any level of structural organization have all of the necessary properties, they should be considered to be autopoietic. In contrast to Maturana and Varela, Hall and his colleagues (Hall 2003, 2005, 2006; Hall et al. 2005, 2009, 2010; Nousala & Hall 2008; Hall & Nousala 2010, 2010a) have argued that autopoietic systems can emerge at different levels of social organization.

Here, I follow Gould's (2002: p. 674) approach for determining whether evolutionary individuals exist at a given level of focus that requires analysis to be limited to levels of the complex hierarchy immediately above and immediately below the focal level of interest[8]. Gould emphasizes that “we make frequent and legendary errors because we tend to extrapolate the styles and modes of our own scale into the different realms of the incomprehensibly immense or tiny in size, vast or fleeting in time” (loc. cit.). Where subsystems of the human body or individual cells are concerned, we are used to distinguishing them with the aid of a magnifying glass or microscope. However, where the systems we participate in as subsystems or particles are concerned, we have great difficulty adjusting our level of focus (Figure 9) to see these supersystems as discrete entities. Mentally, it needs a focal level something like looking through the “wrong” end of a telescope to see the larger world around us at smaller scale.

Our particular interests in this section are levels of focus on structural levels above the levels of cells and multicellular organisms. Hall 2006 discusses other levels of organization such as eukaryotic cells, multicellular organisms, colonial invertebrates

Organizations as autopoietic, cognitive and evolutionary individuals

Organizational autpoiesis

From the human point of view, it is easy for us to see other as autopoietic evolutionary entities – we do this automatically and naturally as part of our normal biological interactions. We can easily see with magnifying glasses and microscopes that people are comprised of living cells organized to produce and maintain people as a autonomous entities. The subsystem/component level is comprised of individual cells forming tissues, organs and organ systems as subsystems required to produce, maintain and reproduce the person. Looking upward, people exist, interact and carry out various roles in an environment composed of a broad ecology and economy of higher level systems. It is more difficult for us to focus on social and economic organizations, to see the people associated with an organization from time to time, together with its premises, plant, equipment, and vehicles etc. as a higher level entity that has as real an existence in nature as people do. In Maturana’s writings, I have found no evidence that Maturana was able to look at living things from different levels of focus as could Gould.

People, tools and machines follow generic laws and regularities to form subsystems, departments and divisions as required to produce and maintain the organization. The organization’s supersystem/environment is determined by higher-level organizations such as governments and economies. In a situated analysis at a higher level of focus, we can then ask whether human economic organizations possess the set of properties that are necessary and sufficient for organizations to be considered to be autopoietic. If so, then various generic properties inferred above for autopoietic systems in general should also apply to organizations. Varela et al.'s (1974) set of properties to be considered are:

- *Bounded* (“the unity [entity] has identifiable boundaries”): People know what organizations they belong to. For the benefit of other individuals and organizations, members are variously tagged with ID badges, bear membership cards, wear uniforms displaying the company logo, etc. Many organizations are physically bounded by “semi-permeable” walls and gates, etc.
- *Complex* (“there are constitutive elements of the unity, that is, components”): Organization members are individually unique, recognize one another as members, and are identified as such within the organization; also machines, property, bank accounts, etc. are identified with tags, catalogued in property registers, etc.

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[8] Nowhere in his immense book does Gould cite either Simon or Salthe – although it is clear that the hierarchy theory that informs Gould’s ideas on multilevel selection must come from at least Salthe’s interpretation of Simon, if not directly.

- *Mechanistic* ("the component properties are capable of satisfying certain relations that determine in the unity the interactions and transformations of these components"): Individuals receive rewards and benefits to belong, and are involved in processes, routines, procedures etc. that the organization conducts to ensure its survival.
- *Self-referential or self-differentiated* ("the components that constitute the boundaries of the unity constitute these boundaries through preferential neighborhood relations and interactions between themselves, as determined by their properties in the space of their interactions"): Rules of association, voluntary allegiance to organizational goals, etc. determined within the organization itself determine what people and property, etc. belong to the organization.
- *Self-producing* ("the boundaries of the unity are produced by the interactions of the components of the unity, either by transformations of previously produced components, or by transformations and/or coupling of non-component elements that enter the unity through its boundaries"): Members are recruited from the environment, inducted, trained, monitored, and managed, etc. Other property and assets are procured and variously integrated into the overall functioning of the organization.
- *Autonomous* ("all the other components of the unity are also produced by interactions of its components as in [the statement above], and … those which are not produced by the interactions of other components participate as necessary permanent constitutive components in the production of other components"): Most organizations outlive the association of particular individuals, and are readily able to replace individual people as they retire or leave and plant and equipment as it wears out.

Certainly, many economic organizations (i.e., firms) undeniably satisfy these criteria to be considered autopoietic. They also qualify as dynamical entities in a thermodynamic sense, dissipating potential as they conduct energy between sources and sinks. Energy processed directly by the metabolism of the organization's human members and its physical machinery plus the large amounts of negentropy abstracted in an organization's book of accounts all qualify in terms of establishing an energy budget (Bailey 2008).

Organizational cognition and knowledge

The next question is whether emerging organizations depend on and build heritable knowledge *at the organizational level* in ways comparable to emerging single cells. Based on substantial work by Hall and his colleagues (Hall 2005, 2006; Hall et al. 2005, 2007, 2008, 2009, 2010, 2011; Nousala & Hall 2008; Hall & Nousala 2010, 2010a; Vines et al. 2007; 2011), the answer is most certainly yes. Knowledge at the organizational level of focus includes such forms as:

- *Structural or "organizational tacit knowledge*" (Nelson & Winter 1982) represented as the physical and cybernetic structure of organizational routines, in connectivity provided by physical layout, organizational jargons, etc, and the building of social and network connections between organizational "positions" that survive the membership of particular individuals in the organization.
- *Personal knowledge* assembled in people's heads relating to their changing roles in the organization that is largely irrelevant to their lives outside of the organization.
- "*Explicit organizational knowledge*" (Vines et al. 2007) existing in "objective" (Popper 1972) formats such as printed and electronic documents within the organization.

Cognitive processes at the organizational level are well represented in the analysis of knowledge intensive procedures (Dalmaris 2006; Dalmaris et al. 2007) and those involved in the formalization of organizational knowledge as described by Hall & Nousala (2010a), Hall et al. (2010, 2011) and Vines et al (2007, 2011).

Organizations as evolutionary individuals

Finally, is it appropriate to consider organizations as evolutionary individuals (i.e., units of selection)?

The first human organizations (i.e., in times before humans became literate and where most knowledge was transmitted genetically, epigenetically – Jablonka & Lamb 1998, 2006, or tacitly – Ong 1982) were probably tribal groups that grew and fissioned where their problem solutions were successful or died out and disintegrated if they made too many mistakes. In the post-Guttenberg era, with the development of literacy and the capacity for objective criticism (Popper 1972, Ong 1982) and knowledge processing technologies humans have become "post-human" (Hayles 1999). The following considerations apply to tribal organizations:

- *Reproduction*: We know from anthropological studies of primitive tribal groups and our near primate relatives that, although there may be some exchanges of people between extant groups, tribes grow through natural increase and fission or fragment if they grow too large; or, if their survival knowledge is inadequate for the challenges they face they may disintegrate or die out entirely.
- *Inheritance*: As described above, tribal groups cohere through their transmission of cultural knowledge as well as the genetic inheritance carried by their people (Ong 1982, Jablonka & Lamb 2006).
- *Variation*: Many sources of variation such as cultural innovation and invention of new tools are available in addition to genetic variation.
- *Interaction*: Tribes certainly interact with one another in areas where they come into geographical contact, where they can trade and compete for status, turf and the natural resources they require to maintain their numbers and cohesion.

There are several difficult issues with modern social organizations is that the nature of modern organizations is changing at least as rapidly as is the nature of the human individuals who coalesce to form organizations. My thinking on this issue is still evolving, but I think it is important to summarize some of the issues impinging on applying autopoietic theory to organizational structures involving humans as components.

In the modern world, what is often not considered when looking at organizations and knowledge from sociological points of view is that literacy and the increasing use of various tools and production technologies to extend human physical capacities have changed many aspects of organizations and organizational governance by comparison to tribal organizations, such that it is useful to consider "socio-technical" organizations comprised of people plus their machines and technologically mediated processes (Harvey 1968). Over the last 30 years, in addition to the ways humans organize to produce physical products, the use of tools such as personal computers and the internet to extend human cognition has even more radically revolutionized the way people interact in organizations (Hall 2006a; Yakhlef 2008). People in today's socio-technical organizations are cognitively knitted together with a wide variety of technologies (e.g., Hall 2006a; Hall et al. 2008) that support distributed decision-making processes extending beyond the mental bounds of human bodies. The result is what Pepperell (1995), Hayles (1999) and Yakhlef (2008) consider to be a "post-human"[9] condition where humans as organisms and their technologies essentially become inseparable. Paradigms from the traditional

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[9] In using the term "post-human" I do not imply any deep philosophical or metaphysical implications, but only the literal fact that aspects of human cognition are extended, distributed, and may even be shared beyond the physical limits of human bodies and brains in ways I discuss in Hall (2006a).

social sciences do not encompass or adequately illuminate this post-human complexity (Yakhlef 2008).

As is the case that individual people are becoming post-human, modern economic organizations (i.e., firms) are also being transformed in similar ways – especially where "reproduction" and "inheritance" are concerned. Ong (1982) argues that pre-literate cultures lack the capacity for rational criticism that in essence involves development of an ability to stand outside of the problem to examine it objectively, and this cannot be done effectively until the words describing a situation can be seen as objective markers for what are otherwise lived, emotional reactions to the world. Tribes react to and coordinate their actions in response to the world in real time. An organization of literate people can objectify observations, study history, analyze situations and plan responses. When the autopoietic organization becomes socio-technical the nature of its reproduction, inheritance and variation change radically. The following considerations apply:

- *Reproduction*: New organizations are formed in a variety of ways, perhaps as subsidiaries or "divisions" of existing organizations. Probably more frequently, new organizations are formed by groups of people (i.e., tested "components") with experience and knowledge from previous organizations who use their knowledge of previous organizations as a template to form a new organization, representing a stage somewhere between coalescence and stable solutions (Nelson & Winter 1982). By comparison to the origins of cellular autopoiesis, emergent organizations can be stabilized by a the availability of a large amount of W3 knowledge on how organizations work.
- *Inheritance*: As described above, both organizational tacit knowledge and many forms of personal and explicit organizational knowledge are readily available to form organizations.
- *Variation*: Many sources of variation are available, including the ability to criticize objective forms of knowledge before applying the knowledge into organizational structure (see Vines et al., 2007, 2011).
- *Interaction*: Organizations certainly interact with one another via their economic activities and compete with one another for staff, material resources, markets and so on.

Thus, socio-technical organizations are probably closer to being some kind of hybrid between coalescent and semiotic (Figure 8) than fitting in any one of these stages. Also, as an issue still to be pondered, an argument may be developed that socio-technical organizations have also developed a form of self-consciousness at the organizational level of focus.

Emergence of autopoietic organizations

Salthe (2004) and Annila & Kuismanen (2009) argue that new dissipative systems can emerge where a system at an intermediate level can increase the overall dissipation of energy flowing from source to sink in the space between existing levels to form a new focal level. Hall et al. (2005), Hall (2006), and Nousala & Hall (2008), Hall et al. (2010; 2011) claim that autopoietic entities can emerge at intermediate levels in an existing complex systems hierarchy and thus form a new focal level. My colleagues and I have studied the emergence of communities of practice within and between larger organizations (Nousala 2006; Nousala et al. 2005), community action groups within areas of urban and regional governance (Hall et al. 2010, 2011), industry clusters within national economies (Hall 2006b; Hall & Nousala 2007), and research groups within larger disciplinary communities concerned with academic and scientific publishing (Hall & Nousala 2010a; Vines et al. 2011).

The process appears to be scalable across different levels of socio-technical organizations is illustrated in Figure 10, Figure 11 and Figure 12. The figures reproduced here specifically depict the emergence of communities of practice, but could be readily modified to depict the emergence of other kinds of knowledge-based autopoietic communities. Referring back to Figure 7, Figure 10, Left represents the evolutionary stage of "turbulence". Figure 10, Right represents "coalescence". Figure 11, Left and Right represent early and late stages in the development of "stable solutions" (i.e., "stable" and "selected"). Figure 12 represents the stage of "semiotic autopoiesis" where objective knowledge is produced available to be shared.

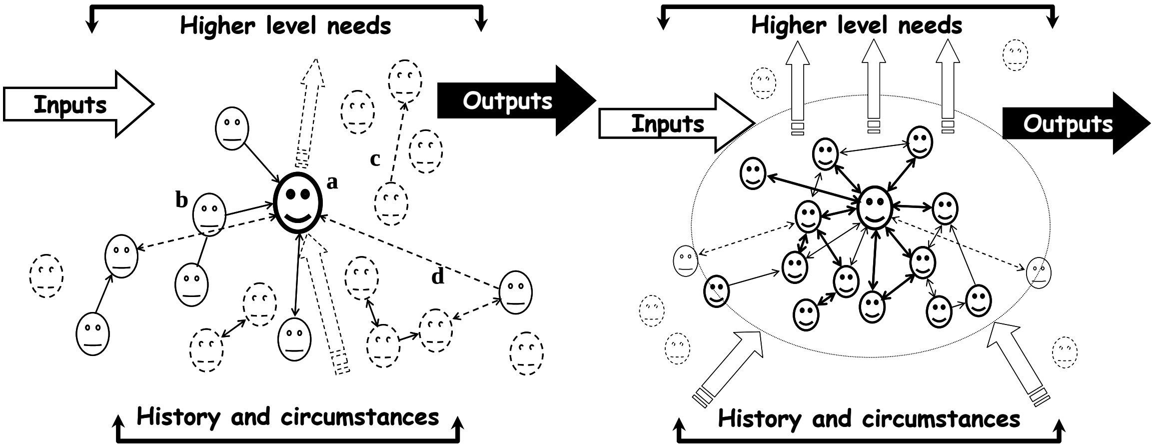

Figure 10. Early stages prior to the emergence of a knowledge-based autopoietic group (from Nousala & Hall 2008). **Left:** A social network created by a "human attractor" (Nousala et al. 2005) within the organization. "Faces" in these figures correspond to people/actors belonging to the organization at the level of subsystems/components (see Figure 9). **a**. A "human attractor" seeking knowledge to address a high-level organizational imperative or need. **b**. Other seekers socially transferring knowledge relating to what the "human attractor" seeks to know for the benefit of the organization. **c**. Other actors in the organization who are not connected to the seeker's current interest. **d**. A knowledge transfer between individual actors. Line weights indicate strength of the connection. The open vertical arrows indicate the possibility that the community may assemble and generate knowledge that will be valuable in addressing organizational needs. **Right:** The coalescence of a community of interest (CoI) around a "human attractor". The human attractor seeks knowledge to solve organizational needs addressing high level imperatives and goals. Bright smiley faces represent people/actors receiving organizational/social rewards for their involvement in addressing the organizational need. Such rewards reinforce the individuals' involvement in addressing the corporate need. Open vertical arrows indicate the value/importance of the assembled, ordered and directed knowledge in addressing higher level organizational requirements. The light dotted line surrounding the attractor's network indicates that participants and others begin to see the network as a community with common interests.

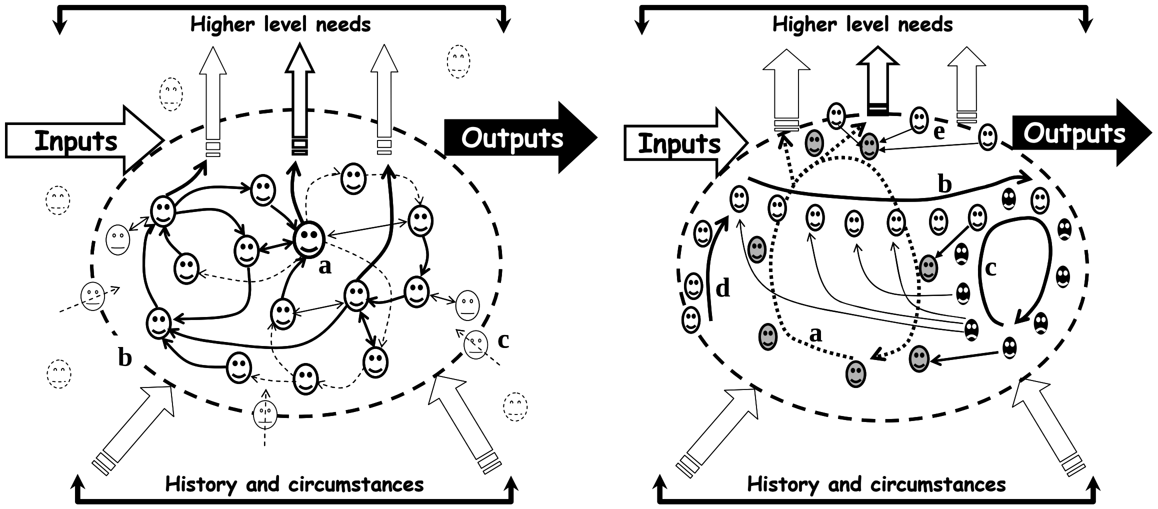

Figure 11. Intermediate stages in the emergence of an autopoietic knowledge-based group (after Nousala & Hall 2008). **Left:** Stabilization around a human attractor. Emergence of processes within a stabilized community of interest. Dashed arrows represent control processes. Solid arrows represent knowledge production processes. Knowledge about how to form and sustain the community is still emerging. **a**. Community facilitator. **b**. Emerging boundary between the system by those who identify themselves as participants in the community (for the purposes of the community only) and others in the community. **c**. Faces crossing the boundary are people in the process of being recruited and inducted into the community. **Right:** Achievement of dispositional autopoiesis. Stage where discrete, self-supporting practices have evolved to produce particular (knowledge) products. **a**. grey faces - internal and external monitoring processes providing overall feedback control to maintain and sustain the community. **b**. white faces - a production process delivering a product to the broader organizational environment. **c**. product quality control cycle provides corrective feedback to the production process. **d**. induction process recruiting new individuals into the community to satisfy new needs and to replace attrition. e. environmental monitoring to feed observations into monitoring and control process. Note, this evolutionary stage still depends on tacit routines and tacit knowledge/acceptance by individual participants of their learned roles in the routines.

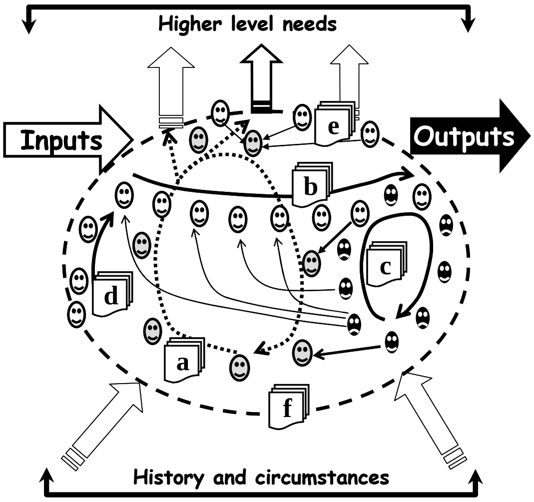

Figure 12. Semiotic autopoiesis (after Nousala & Hall 2008). State where the practices to form and maintain the community have been objectified and documented (as indicated by the records icons). Grey faces – those following codified knowledge (**a**.) about how to manage internal and external monitoring processes providing overall feedback control. White faces – those following codified knowledge (**b**.) about the production process. Black faces – those following codified knowledge (**c.**) about the product quality control cycle. **d.** codified knowledge about induction process recruiting new individuals into the community to satisfy new needs and to replace attrition. **e.** codified knowledge about environmental monitoring processes. **f.** codified knowledge about how to establish and sustain the community itself.

AUTOPOIETIC COGNITION TO CONSTRUCT HUMAN AND HUMAN SOCIAL KNOWLEDGE

I have discussed in the physical framework developed here how structural knowledge evolves as a consequence of natural selection as Maturana and Varela (1973 [1980: p. 119]) stated that,

> …knowledge … is necessarily always a reflection of ontogeny of the knower because ontogeny as a process of continuous structural change without loss of autopoiesis is a process of continuous specification of the behavioral capacity of the organism, and, hence, of its actual domain of interactions. Intrinsically, then, no absolute knowledge is possible, and the validation of all possible relative knowledge is attained through successful autopoiesis.

It remains to explore from the physical realist framework developed here how cognitive processes in autopoietic systems construct knowledge. Popper's (1972) "general theory of evolution" provides a broad outline, but no guidance as to how the cognition of autopoietic systems evolves from the feedback regulation of structural organization necessary to compensate for perturbations to the system. To do this I will begin with Boyd's OODA loop (1992; Osinga 2005 - Figure 13), originally developed to describe cognitive processes carried out by individual humans or organizational units in combat. Boyd was an exceptional jet fighter pilot and combat instructor during and after the Korean War and a aircraft design engineer who studied physics, biology and philosophy (including Popper's earlier epistemological works) in his spare time (Osinga 2005).

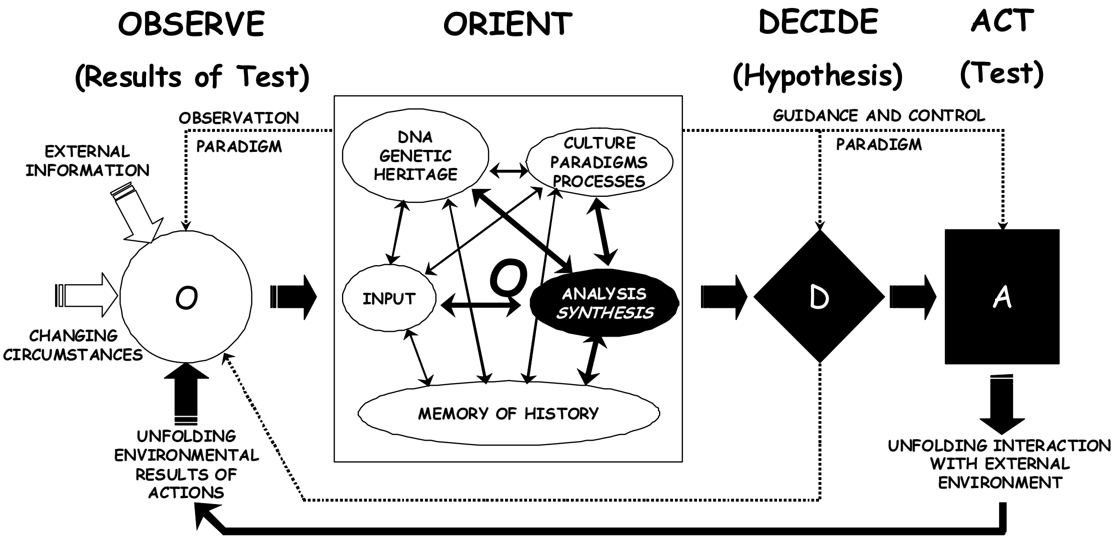

Figure 13. Boyd's OODA loop process (Hall 2003 after Boyd 1996).

The OODA loop is his distillation of the cyclic cognitive activities required for a living entity with some form of consciousness to construct and maintain an adaptive understanding of the world. This is described in detail and in some cases extended (Grant 2005; Grant and Kooter 2004; Hall et al. 2007; Ullman 2007). In the terminology of autopoiesis as illustrated in Figure 14, "Observation" represents internal disturbances triggered at the autopoietic boundary by environmental perturbations. These are processed during the "Orientation" phase that also includes "sense-making" and "planning" functions (Grant & Kooter 2004). "DNA/Genetic Heritage" represents the capabilities that are essentially fixed in the structure of the developed entity.

"Culture/Paradigms/Processes" represents tacit knowledge. "Analysis/Synthesis" represents the processes of innovation and review to explore options and their possible consequences based on the memory of history. "Decision" represents the selection of a particular option to implement. In some cases, the decision may be to do nothing. As Ullman (2007) and Hall et al (2007) note, no decision is often worse than a "bad" decision. "Action" is the application of the internal decision onto the external world via effectors. Note the feedback loops, especially that relating to observations of the unfolding responses of the external environment to actions just applied. It is through this continuing cycle of decision, action and observation that orientation constructs an increasingly functional understanding of the world.

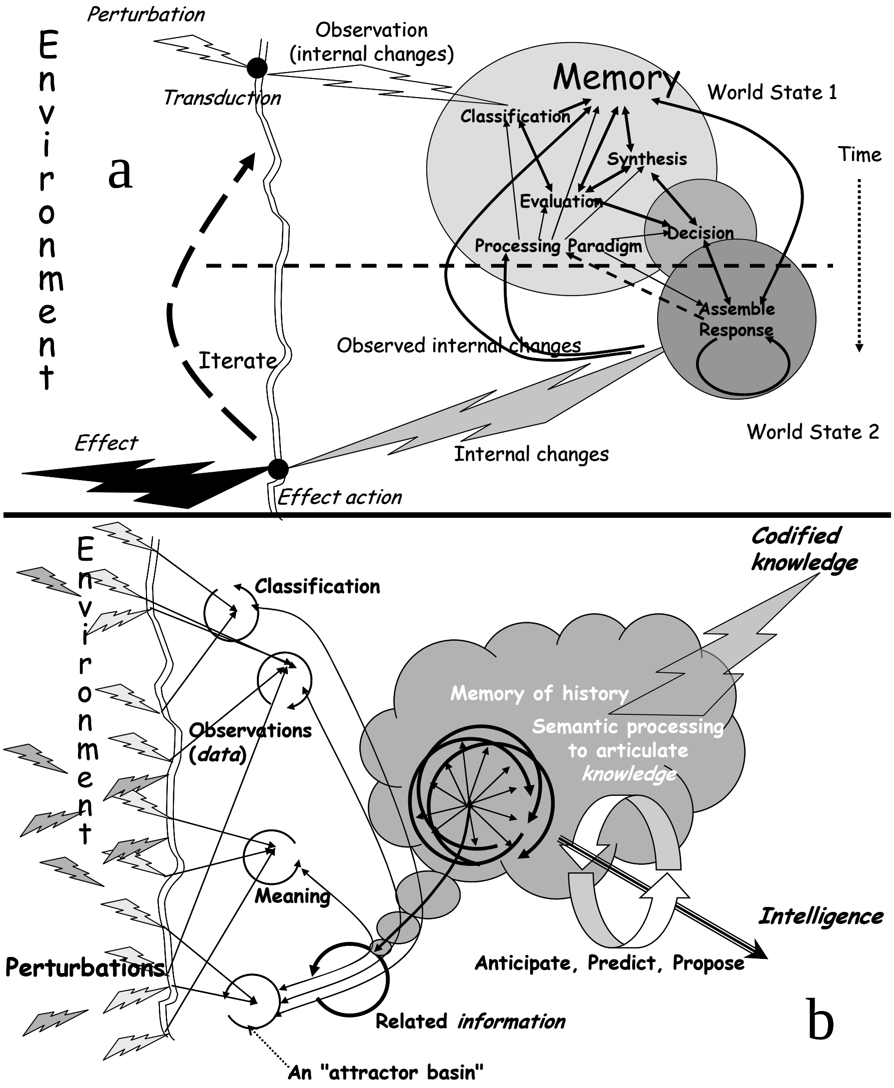

Figure 14. Two depictions of the operation of an OODA cycle within autopoietic systems (after Hall et al. 2005). The double line represents the boundary between the environment on the left and the autopoietic system. Panel a shows the sequence of dynamic effects as a perturbation from the world is transduced into disturbances that propagate through the entity and how sense is made of the disturbances in relationship to the entity's prior history, to synthesize one or more possible responses, and to select and apply one of these responses as internal changes that effect an action on the world. Panel b shows a somewhat more detailed depiction of the specifically cognitive aspects of observation and orientation in the OODA cycle involving many simultaneous perturbations (e.g., many photons falling on a retina) and the way these are classified and processed to give meaning. Note: PowerPoint animations of these graphics

(beginning with slide 11) are available on http://tinyurl.com/3y6n4y and may clarify the dynamical sequencing of processes.

Figure 15 illustrates the framework of autopoietic cognition as the entity seeks to solve a survival problem (Hall et al. 2007) in the "evolving block universe" (Ellis 2006, or "crystallizing block universe, Ellis & Rothman 2010). The horizontal arrow represents a sequence of instants along the time axis. The two dimensions of the page represent 3D space. "Immutable past" represents the fixed block of the past that progresses towards a "stochastic future" that can be reached from the "instant of becoming – now" via an adjacent possible timeline (Kauffman 2000, 2003; Kauffman et al 2008). The entity faces a problem of life (Popper 1972), where the "problem solution" represents a particular solution that will allow the autopoiesis to continue. Many of adjacent possible timelines will lead to "divergent futures" where the problem of life is not solved. Here we are considering an entity that has the capacity to anticipate what that problem solution might be in order choose among the adjacent possibles to select one that seems directed towards the problem solution. Hall et al. (2007), Martin et al. (2009) and Philp and Martin (2009) explore the means by which entities interact with the world to select among adjacent possible timelines to converge on the problem solution (indicated by the "temporal convergence" arrow).

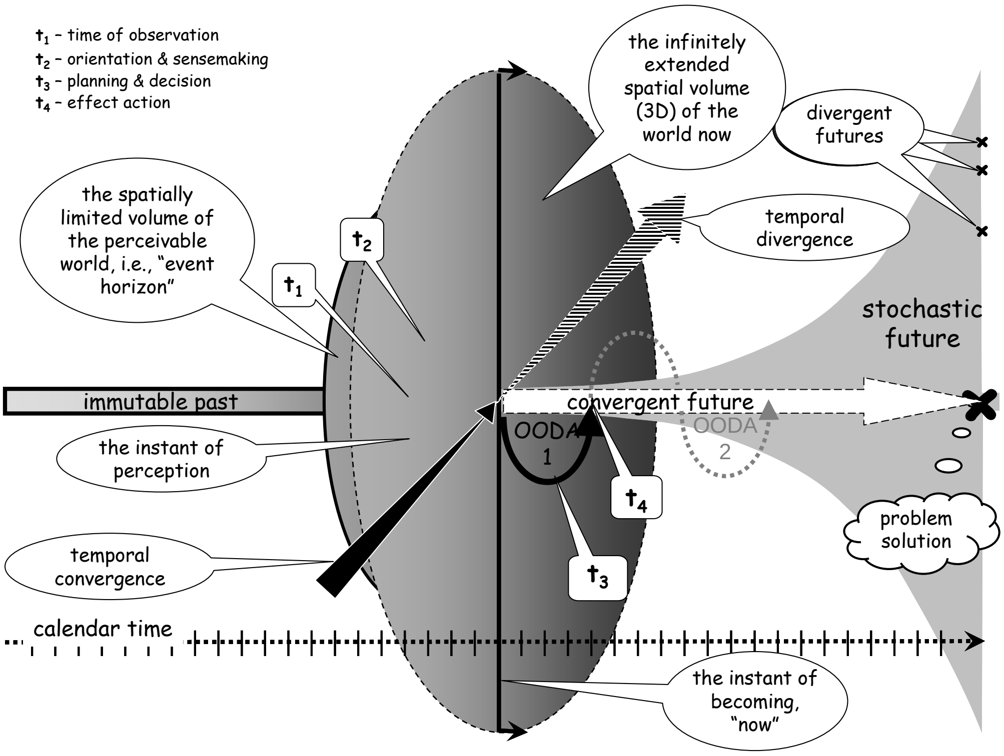

Figure 15. Autopoietic observation and action in Ellis's (2006) "evolving" or Ellis & Rothman's (2010) "crystallizing block universe (Hall et al. 2007).

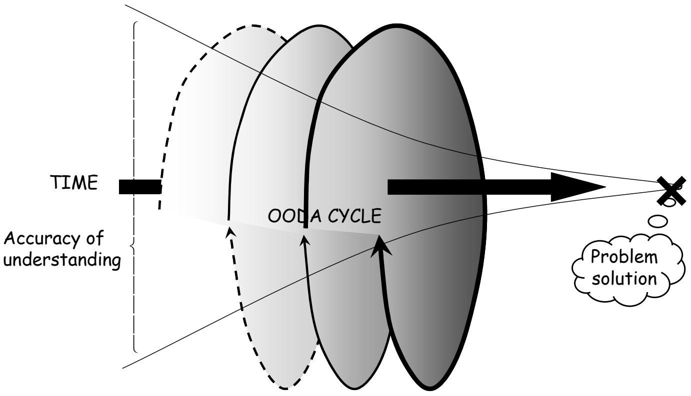

Figure 16. Refinement of knowledge via the OODA cycle as a problem solution is approached.

The diagram (Figure 15) makes it clear that knowledge of the world constructed via the OODA cycle (Figure 16) is always out of date. The external world in which autopoietic systems live is dynamic and continually changing, both as a consequence of blind entropically driven processes, and the active and sometimes conscious interventions and changes made by other autonomous actors in the space. None of the cognitive processes required to transform observations of external reality into a constructed image or model of the world are effortless or instantaneous.

Boyd loops are iterated in time, and each transduced disturbance from the external world can start a new loop, such that different loops can overlap in time to continuously update memory. With regard to particular Boyd loops, four points in time can be defined in a relentlessly changing world: $\mathbf{t}_1$ is the point in time when perturbations from the environment (Figure 14) impinge on the autopoietic boundary and are transduced into internal disturbances. This is defined as the “instant of perception”, and as indicated this instant of perception samples only a small part of the world, i.e., “the spatially limited volume of the perceivable world” or the “event horizon” or the “cognitive edge” (Day & Schoemaker 2004). Note that the event horizon is determined by what the entity can perceive, not the external world. $\mathbf{t}_2$ is the range of instants through which orientation and sense-making take place. This begins with the classification of observational perturbations and includes processes by which these are compared with the memory of prior history and evaluated. Possible actions are synthesized and criticized based on the developing understanding of external circumstances. $\mathbf{t}_3$ is the range of instants during it is decided either to execute a particular action or to continue constructing situational knowledge; $\mathbf{t}_4$ is the point at which the decision is effected upon the external world.

Observations relate directly to the state of the world only at the time when they are made (i.e., at $\mathbf{t}_1$ when external stimuli are transduced into the sensory contents of observations). Even then, internally propagated sensory data triggered by the world is an idiosyncratic and fallible representation of the external reality depending on the capabilities of the transduction apparatus and processes (Ullman 2007). Further cognitive processing is required to filter, classify and evaluate sensory data against memories of prior observations (i.e., to detect changes) to construct a cognitive model at $\mathbf{t}_2$ of what was observed. This takes additional time. Further delays are introduced in deciding and acting. To compensate for this, individual humans consciously and unconsciously build dynamic world models in their minds for themselves and for their organizations that project regularities and trends through time so as to anticipate what the world may be like when an action is decided (Riegler 2001, 2001a, 2003; Butz et al. 2004, 2004a).

However, as the entity approaches the time by which the problem solution is required, the accuracy of the constructed understanding may converge towards this via repeated OODA cycles. The inexorably progressing world at an instant of “becoming”, i.e. “the infinitely extended spatial volume (3D) of the world now”, is depicted by the large disk.

AUTOPOIESIS, DOWNWARD CAUSATION AND FREE WILL

The OODA analysis makes it very clear that the world an autopoietic entity acts on is never the same oneperceived. For individual humans, actions we have to think about (i.e., not reflexes) involve seconds to minutes between observing and acting on the observation. Even in the case of distributed cognition (Hutchins 1995) at the organizational level, where responses take place more-or-less as “routinized” organizational reflexes (Nelson & Winter 1982; Amaravadi & Lee 2005), organizational responses will take many seconds to minutes. Where observing, orienting, deciding and acting require conscious social interactions, organizational responses are bound to take many minutes to hours or even days before an OODA loop can be completed with an action.

If time and change unfold on the basis of quantum mechanical interactions how can such slow processes achieve intended futures in a relentlessly unfolding world?

The key is to apply knowledge in ways that constrain and affect the spatial relations of fundamental physical particles (e.g, Ellis 2006, 2006a, 2008; Ellis & Rothman 2010). The following speculative argument is a worst-case sketch of how decision can still be applied in/by autopoietic systems even if the choice between alternative futures can only be effected at the level of quantum interactions in single instants of Planck time.

A physical example clearly demonstrates how macro level spatial controls can directly affect quantum level interactions:

Uranium-235 (U235) atoms have a half-life of ~700 million years against spontaneous decay to form Thorium 231 with the release of an alpha particle (helium nucleus) and energy[10],[11]. Quantum mechanically, there is no way to tell if a given atom of U235 will decay in the next minute or in a billion years from now. However, if a fast neutron is absorbed by the nucleus of a U235 atom, the atom fissions within a femtosecond (10-15 sec) into two large fragments, 2-3 neutrons and a lot of heat energy (Halperin 1959). In nature today, free neutrons are rare and U235 atoms are so widely separated that the chance that one atom will absorb a neutron released by the spontaneous fission of another is essentially zero. However, humans have demonstrated the capacity to refine and physically concentrate U235, and quickly assemble enough atoms close together into what is called a “critical mass”. If there are enough U235 nuclei within close range, when one nucleus fissions, other nuclei will absorb neutrons released by the fission event, and also immediately fission. This leads to a “chain reaction” that releases enough energy within microseconds to cause a nuclear explosion.

In general, the spatial distribution of particles is quantum mechanically determined by their spatial distributions and interactions in the previous instant, i.e., their present positions and possible futures are substantially constrained by their past histories. Thus, as discussed earlier in this paper, the present configuration depends on the past that quantum mechanically determines what is possible and probable in the next instant.

Although not as dramatic as building an atomic bomb and pushing a button to cause it to explode, to remain viable even the simplest emerging autopoietic systems enforce

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[10] http://www.eoearth.org/article/Uranium.

[11] http://www.world-nuclear.org/education/phys.htm

downward causation on the underlying quantum and atomic level of organization from which they emerge. Autopoietic systems are organizationally (Maturana & Varela 1980) and semantically (Pattee 1995) "closed" systems that are self-determined by their structures (Hall 2006). Systems are autopoietically integrated when their instantaneous organization is such that the positions and dynamics of their particles in phase space perpetuates autopoiesis into the next instant, again as discussed earlier. Thus, the structural organization of the autopoietic system retains an historical trace of its past autopoiesis (the simplest form of self-reference). However, if this structure is perturbed in a way such that its structure and dynamics no longer maintains autopoiesis, the system dis-integrates and its thread of history is lost. As autopoietic lineages vary, natural selection leads to the evolution of compensatory control information allowing the autopoietic entity to regulate its structure in ways that allow it to survive certain kinds of perturbations. Pattee (1995) expresses it this way,

> [S]elf-reference that has open-ended evolutionary potential is an autonomous closure between the dynamics (physical laws) of the material aspects and the constraints (syntactic rules) of the symbolic aspects of a physical organization only by virtue of the freely selected symbolic aspects of matter do the law-determined physical aspects of matter become functional (i.e., have survival value, goals, significance, meaning, self-awareness, etc.).

"Closure" refers to the fact that dynamic activities of the autopoietic system serve to maintain its autopoiesis, where autonomy is a key character of autopoiesis. By "symbolic aspects" Pattee is referring to control information (knowledge) encoded in the structure - as elaborated and clarified by Corning (2001) and Hoffmeyer and Emmeche (Hoffmeyer 2000, 2002; Hoffmeyer & Emmeche 1991; Emmeche 1998, 2000, 2004). Collier (2006: 2) says,

> A system is autonomous if it uses its own information to modify itself and its environment to enhance its survival, responding to both environmental and internal stimuli to modify its basic functions to increase its viability.... an organism will not last long if its functioning does not contribute well to its autonomy; it will be selected against by natural selection.

As noted, this "information" may be no more than an historically determined structure that happens compensate for a perturbation that would otherwise disrupt the system. Where the self-maintaining structure is disrupted, this structural history is lost. Thus, selection operating on autonomous systems will lead to the growth of "dispositional" knowledge in the form of structural solutions to solve the problems of life. As new solutions are added to old ones, surviving lineages exhibit increasingly sophisticated and robust forms of compensation, including various forms of anticipatory responses. This is where the OODA loop processes begin to emerge.

In emerging autopoietic systems, dispositional knowledge (W2) is embodied in the instantaneous physical and dynamic structure (Urrestarazu 2004). In systems at the molecular/cellular level this embodied knowledge exists in the positions and properties of the systems' macromolecules and other components and contents. In human organizations, substantial knowledge is embodied in 'organizational routines', layout of plant and equipment, social and communications networks, etc. (Nelson & Winter 1982). In today's living organisms (including humans), natural selection has led to the evolution of a sophisticated genetic apparatus for the hereditary transmission, storage, replication (in DNA), transcription (into RNA) and translation (into polypeptide sequences) of large amounts of codified or “objective” knowledge (Popper 1972). Genetic knowledge is built through natural selection rather than specific encoding processes (Hall 2006). For humans and human-based organizations, objective knowledge is consciously encoded, transmitted, stored, replicated and applied via writing and electronic means (Hall 2006a; Jablonka & Lamb 2006).

At the quantum mechanical level, impulses resulting in cognition are transmitted through the organized structure of an organism as "disturbances", propagating as the spatial and dynamic organization of particles (and photons) in one instant affect the organization of adjacent particles in the next instant (Figure 14, Figure 15). Spirally cyclic chains of such disturbances provide the opportunity to feed back results from applying control information, but there is always delay as the disturbances propagate physically through a sequence of instants, such that the cycle is an open spiral through time rather than a closed circle in an instant (Figure 16). The fact that impulses are coherently propagated and processed in cognitive processes that are adaptive for the organism is a consequence of billions of years of natural selection. In time this has led to the emergence of consciousness, self-awareness and an “executive” function (Donald 1997, 2001) able to recognize problems and generate, criticize, decide and apply tentative solutions to manage problems (Popper 1972), bearing in mind that “decisions” trace back to the “willful” application of constraints at the quantum level favoring one possible future over another, and that the constraints will be built up by the propagation of disturbances in the cognitive system over a succession of many instants radiating out from the instant of decision (Ellis 2008; Figure 15).

In lower organisms with no consciousness, where the “decision” function is natural selection, the OODA spiral’s cycle time is a generation. The evolution of a living memory of the past combined with the capacity for conscious self-reflection enables many cycles of criticism and decision making within a lifetime or even relating to a specific time bound problem situation to conceive intended futures and to shape the world to reach them. Social coordination of many people within organizations provides even more tools for controlling the world to reach intended futures. The implementation of information systems and other cognitive tools, if used effectively, substantially increases span and detail of the perceivable event horizon and the bounds of rationality (Hall 2006a). The organizational OODA cycle is the product of many individual human OODA cycles as these are connected via organizational routines (i.e., organizational cognition) to form a larger order OODA cycle responding to organizational imperatives.

CONCLUSIONS

As mentioned in the introduction, Maturana and Varela’s concept of autopoiesis claims to be a necessary and sufficient definition for the phenomenon of life. As such it should a basis across the life sciences for understanding and analyzing many aspects of living systems. Unfortunately, because of an excessively paradigmatic language and their failure to develop a compelling logic relating autopoiesis to the physical world, and then failing to use the concept to provide deep explanations for aspects of life and the life sciences.

In this paper, I think I have shown how the phenomena of autopoiesis and cognition defined as physical phenomena by Maturana (1970), Maturana and Varela (1973) and Varela et al (1974) emerge spontaneously as logical consequences of the structure-determined survival of certain adjacent possible timelines (Kauffman 2000, 2003; Kauffman et al 2008) compared to others.

The emergence of improbably complex systems results from the dynamical interactions of particles dissipating potential in fluxes of energy flowing between high potential sources and lower potential sinks. Knowledge, in the sense of self-regulatory control information embodied in instantaneous structure (or Popper's 1972 solutions to problems), emerges simultaneously with autopoiesis and cannot be constructed without the operation of some form of selection working on or within autopoietic systems to eliminate structural configurations along adjacent possible timelines that fail to provide adequate compensation for perturbations. Similarly, autopoietic closure cannot continue through time in the face of perturbations without some form of structurally embodied knowledge. In summary to this point, given the laws of physical dynamics and thermodynamics, autopoiesis and autopoietic knowledge will emerge wherever in the Universe the chaotic dynamics of particles and energy flows allow the assembly of sufficiently complex dynamic systems to support the cyclic dissipation and storage of potential able to regulate dissipation rates. Such systems need not be limited to aqueous molecular assemblages.

Once given a picture of autopoiesis firmly and unambiguously rooted in the physical world, I think I have demonstrated in the present and related papers that this understanding of autopoiesis provides for the conceptual unification of the epistemology, genetics, and the life, behavioral, social sciences, and the information systems and organizational knowledge management disciplines within the framework of evolving hierarchically complex systems (Simon 1962, 1973, 2002; Miller 1978; Koestler 1967, 1978; Beer 1979, 1981, 1984, 1985; Salthe 1985, 1993, 2004; and Gould 2002). I have also argued that autopoietic systems can evolve and maintain themselves at several levels of organization including that of human groups and economic organizations.

I have shown here and elsewhere, that there is a reasonable evolutionary pathway from knowledge embodied in autopoietic structure (Popper's world 2) to codified knowledge existing persistently and relatively inertly in nucleic acids (Poppers world 3), and from human tacit knowledge (W2) to various kinds of explicit or objective knowledge pertaining to the maintenance of the autopoietic organization such as documents, contents of computer memories, etc. (W3). All forms of W3 knowledge are cognitively constructed by autopoietic entities[12]. Codified knowledge is only given meaning when it is decoded and embodied in the structural dynamics of autopoietic systems.

Finally, I think an understanding of the physical basis for autopoiesis without any metaphysical or supernatural components provides a rational basis for a kind of free will that can be applied by any self-conscious entity.

To conclude, I think Maturana's ideas on the nature of living things and their cognition have been ignored by the world of science at large for much too long. This is understandable given the difficulties with his paradigmatic language and the minimal connections and comparisons with other realms of biology via references that would have helped breach the boundaries of paradigmatic incommensurability. In this paper I have tried to restate the concepts in the conceptual domain of physical dynamics and build bridges across chasms of incommensurability between Maturana's constructivism and a number of other more widely understood paradigms.

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[12] With the construction of increasingly sophisticated computer systems, this distinction is beginning to be blurred.

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