A Biological Theory of Knowledge and Applications to Real World Organizations

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Abstract

This paper extends an epistemologically grounded biological theory of organization and knowledge based on Karl Popper's evolutionary epistemology and three worlds ontology, amalgamating concepts from evolutionary biology, emergence and hierarchy theory, autopoiesis, and military affairs. We discuss how this body of theory is being used to guide and inform KM research and development in a geographically extended industrial and project management organization. Applicability of the biological and epistemological framework is demonstrated in a study of the emergence and sustainment of communities of practice, in the development of a methodology for improving business processes, and in the implementation of managing engineering knowledge over the lifecycles of fleets of ships and vehicles.

1. Introduction

The science of biology is founded in Darwinian evolutionary theory (1859), Mendelian genetics (rediscovered and understood in 1900), and biochemical metabolism, molecular biology and biochemical genetics (from the mid 1940s and 50s). By comparison, the knowledge management discipline still lacks a physically based and commonly accepted theory of knowledge. Compared to biology, it is still practicing what is the equivalent of pre-Darwinian "natural history". This can be revealed in any KM practitioner forum by asking what it is they study. The issues in organizational science are equally dire (McKelvey undated). However in the last decade or so some concrete progress has been made towards a scientifically grounded theory of organizational knowledge. This paper reviews the nature of a foundational framework the authors of this paper are developing from physically based biology, and presents our early attempts to apply aspects of the framework in an engineering knowledge management environment.

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Varela et al (1974) and Maturana and Varela (1980; 1987) introduced "autopoiesis" (= self production) as a term for the minimum set of properties entities must have to be considered living. Von Krogh and Roos (1995) and Magalhaes (1996, 1998, 1999) suggested that human organizations might be autopoietic. Hall (2003a, 2005) took the idea further, basing his ideas in Karl Popper's epistemology (1972; 1994), hierarchical complexity theory (Pattee 1965 and later; Simon 1962, Salthe 1985, 1993), non-equilibrium thermodynamics (Prigogine 1955; Morowitz 1968; Kay 1984; Schneider 1988; and Schneider and Kay 1994) and evolutionary biology (Gould 2002). Evolving (and hence autopoietic) entities may exist at several levels in the structural hierarchy of life from cells to social systems (Simon 1962, Salthe 1985, 1993; Gould, 2002; McShea & Chanqizi 2003). Organizations such as firms have "hereditary" properties transcending those of their individual members (e.g., Nelson and Winter, 1982), justifying their treatment as evolutionary individuals. Hall (2005) argued that organizational learning and knowledge growth were inevitable products of autopoietic processes in living organizations.

This paper graphically extends Hall's (2005) formulation. Autopoiesis and the origin and evolution of knowledge are first described in general terms applicable to complex organized entities. We then argue that at least some human social organizations have the necessary properties to be considered autopoietic. We conclude by describing how the theory applies to some real-world cases we are studying in a large engineering project management organization.

It should be noted that McKelvey (1997, 1999, 1999a, 1999b, 2001, 2002, 2004; McKelvey & Baum 1999; Henrickson & McKelvey. 2002) is also working to establish a critical scientific realist framework for organizational studies. Similar to the approach we take here, McKelvey bases his approach on evolutionary epistemology (Donald Campbell's version), non-equilibrium thermodynamics, evolutionary biology, complexity theory and concepts of "organizational heredity" as introduced by Nelson and Winter (1982). We come to broadly similar conclusions, but by analyzing our differences we should more closely approach the underlying truths of organizational dynamics. Unfortunately it is beyond the scope of the present sketch to compare the two approaches here in any detail.

2. Autopoiesis and Emerging Systems in a Complex Hierarchy

Autopoiesis and the autopoietic (biological) theory of organizational knowledge are not yet well known in the knowledge management discipline. Thus, we begin by reviewing the basic concepts. Defined in one sentence, *autopoiesis is the emergent condition achieved by a system of bounded (i.e., self-identifying), self-regulating set of dynamic processes able to maintain its existence as an autonomous entity in the face of environmental perturbations*; i.e., that which qualifies a complex dynamic entity as "living". Varela et al. (1974) listed six criteria (summarized here), which together they considered to be necessary and sufficient for a system or complex entity to be considered to be autopoietic or living:

- *Self-identifiably bounded* (demarcated from the environment by membranes, or the entity's components are identifiably tagged)

- *Individually identifiable components within the boundary* (complex)
- *Mechanistic* (i.e., driven by cybernetically regulated energy fluxes or metabolic processes)
- *System boundaries internally determined* (self referential)
- *System intrinsically produces own components* (self production)
- *Self-produced components are necessary and sufficient to produce the system* (autonomy).

Von Krogh and Roos (1995) quote the Varela et al. (1974) list, and Maturana and Varela (1980; 1987) provide more extensive discussions of the concept. Hall (2005) observes that these criteria do not consider time as a factor, and argues that for the concept of autopoiesis to be meaningful in real-world contexts, *an autopoietic entity must be able to self-maintain its state of autopoiesis over a period of time*.

In a physical sense, an autopoietic system (i.e., a living entity) is an autonomously self-regulated complex system of dynamic cyclical processes. These are driven and maintained far from thermodynamic equilibrium by the "forced" transportation of fluxes of matter and energy between high potential (high exergy[2]) through the system to sinks of lower potential (high entropy, Prigogine 1955, 1981; Morowitz 1968; Kay 1984; Schneider 1988). Such systems are self-organizing and emergent (Salthe 1985, 1993; Schneider & Kay 1994, 1995; Jorgensen 1999; Giampietro et al. 1999; McKelvey 2004). Kauffman 1993 reviewed and summarized a wide variety of mathematical, chemical and biological models demonstrating the emergence of organized (i.e., ordered) structure at the "molecular" level from initially more chaotic or random states.

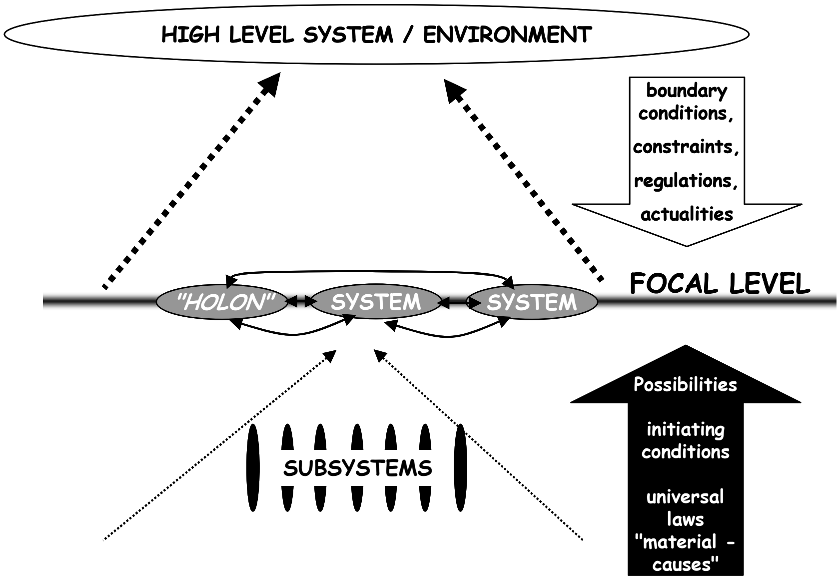

Figure 1. The systems triad in hierarchy of complex dynamic systems (after Salthe 1985).

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[2] Those unfamiliar with the term exergy may wish to consult Wikipedia - http://en.wikipedia.org/w/index.php?title=Exergy&oldid=19074539

As summarized in **Figure 1**, the world is hierarchically complex (Simon 1962): quarks form subatomic particles, that form atoms, that form molecules, that form macromolecules, that form prokaryote cells or organelles, that form eukaryote cells, that form tissues, that form organs, that form organisms, that form social organizations and species, that form ecological or economic communities, that form ecosystems and economies, that form the biosphere, that form a larger dissipative system involving the sun, the biosphere and space, and so on up to an environment forming the whole universe.... Salthe (1985, 1993, 2004), Wu (1999); Emmeche (1997); Emmeche et al. (1997), Chaisson (2001), etc., explain how instabilities in the fluxes from high to low potential can lead to the origin and emergence of new levels of complexity in such hierarchical systems. So complex in fact, that the state of a higher level in the hierarchy cannot be deterministically computed even from the next lower level, and that details of its emergence cannot be predicted from the initial conditions of its components (Polanyi 1968; Davies 2004). (Such uncomputability does not imply that it is impossible to describe analytically after the fact how a particular state of the higher level system arose from the lower level.)

Following Salthe (1985, 2004), the state of a complex system can be analyzed and represented as a triad consisting of:

- A "*holon*" at the "focal level" of complexity (i.e., the level of interest in the hierarchy) is the dynamic system where we focus our analysis.
- *Lower-level components or subsystems forming the holon determine what the holon is and what it can do*. Component/subsystem capabilities are described by "universal" laws (i.e., "material causes") that are independent of the circumstances of any particular holon they may participate in forming.
- *Higher level supersystem or environment containing the holon as a component. What the holon actually does* is a consequence of its own past history and being, as shaped by boundary conditions and constraints imposed by the higher level ("formal cause").[3]

3. Karl Popper and the evolution of organic knowledge

In his later works, Karl Popper explored two themes that provide foundation stones for a biologically based theory of knowledge: (1) knowledge grows through variation (Campbell 1960), combined with the selective elimination of errors (e.g., through criticism)[4]; and (2) a division of the universe into three ontological domains or worlds. Popper first expressed these mutually supporting themes in the papers collected in his book, *Objective Knowledge:*

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[3] One area where we differ substantially from McKelvey (2002, 2004), is that McKelvey attempts to drive the emergence of coarse grained structures at the organizational level directly from the quantum level of organization. By contrast our reading of Salthe's theory of emergence is that fast, small, entangled properties of the quantum layer are completely subsumed in the multiple layers of hierarchical organization between quantum and organization. From a point of view in the organizational layer, we are only directly concerned with laws governing properties and interactions of organizational components such as people.

[4] It should also be noted that we regard Popper's construction of evolutionary epistemology to be more fundamental, and thus easier to apply, than Campbell's (as ably reviewed by McKelvey (1999) and McKelvey & Baum (1999)).

An evolutionary approach (1972). Although Popper's approach is philosophical, not biological, his numerous references to knowledge in lower forms of life makes it clear that he considered knowledge to be an emergent product of life.

Popper's most expansive expression of his "evolutionary theory of knowledge" was as a "general theory of evolution" (Popper 1972 pp 241-244 - **Figure 2**).

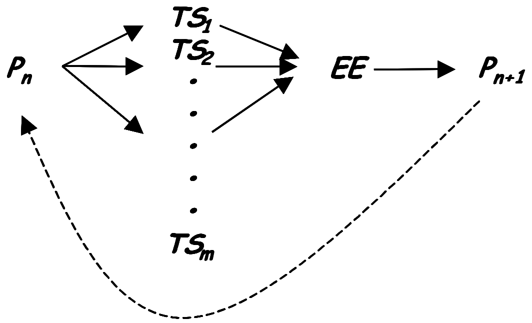

Figure 2. Popper's "evolutionary theory of knowledge" (after Popper 1972: pp. 243). We add the inferred iteration loop to the drawing.

P_n refers to a problem situation encountered by a living entity or species of entities; TS_i $_{(i = 1, , , m)}$ refers to tentative solutions or theories offered or proposed by the entity or entities; ***EE*** refers to a process of error elimination, by which failed solutions or the entities implementing failed solutions are selectively removed; and P_{n+1} refers to the 'new' problem situation existing after P_1 has been solved. Where knowledge cannot be expressed linguistically, i.e., where the knowledge is embodied in the disposition of the entity, the entity itself is eliminated if the tentative solution fails. However, where theories are expressed linguistically, they can be consciously criticized and eliminated prior to acting on them, to let the theory die instead of the entity. Elsewhere Popper normally refers to this as his "tetradic schema", $P_1 \rightarrow TT \rightarrow EE \rightarrow P_2$, where ***TT*** is rendered as "tentative theories" rather than tentative solutions. This construction is appropriate for discussing criticism of linguistically expressed theories rather than embodied solutions.

We are unaware that Popper ever compared his epistemology to radical constructivism (von Glaserfeld 1984, 1993, 1997, 2001; de Zeeuw 2001; Riegler 2001). However, Popper accepts that knowledge of the world is constructed, and that claims to know can never be proven to be true. But, unlike constructivists, Popper's epistemology assumes that external reality exists as a fiduciary principle against which claims may be tested (Niiniluoto 1999; McKelvey 1999b; Firestone & McElroy 2003a). He argues that knowledge can grows to more closely represent external truth by iterated tests of claims against reality to eliminate those that erroneously predict the consequences of the test. What survives is an improved construction of reality.

Hall (2003a, 2005) offered John Boyd's (1996) OODA loop (Figure 3) as a representation of Popper's general theory of evolution. Boyd's acronym stands for Observe, Orient, Decide and Act. For Boyd, this summarized how an individual or organization solved the life and death problems of surviving in a competitive environment.

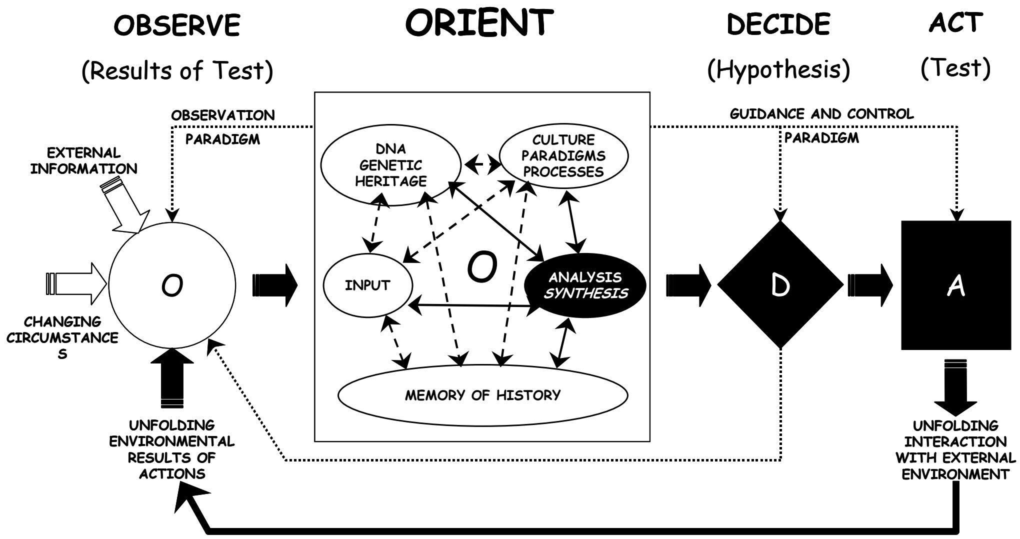

Figure 3. John Boyd's OODA Loop concept (from Hall 2003a, after Boyd 1995).

Boyd was an ace fighter pilot in the Korean War and became a respected military tactician and strategist. He did not document his epistemological sources, however, Boyd's personal papers (Anon. undated) include Popper's Logic of Scientific Discovery (1959) and Conjectures and Refutations (1963) - annotated by Boyd, as well as the 1993 printing of Radnitzky and Bartley's Evolutionary Epistemology, Rationality, and the Sociology of Knowledge (1987), which includes contributions from Popper. We assume Boyd drew his inspiration from Popper and his pragmatic experience in the real world of armed combat. The OODA loop represents a generic adaptive learning process for any autopoietic entity applying Popper's evolutionary theory of knowledge.

Definitions below are derived via Hall (2003a) from Coombe (1996, 1999), who used Boyd's concepts in his own work.

- *Observation* assembles *data* about the world (including the entity's own effects and those of its competitors on that world). Data given context relating to interactions with the world becomes *information*.
- *Orientation* processes information from those observations into semantically linked *knowledge*[5] to construct a world view comprised of
    - recent observations,
    - memories of prior experience (which may be explicit, implicit or even tacit),
    - genetic heritage (developed dispositions based on inherited genetic code),
    - cultural traditions (i.e., also including paradigms - Kuhn 1970, 1983) in individual humans or human organizations), and
    - analysis (destruction and criticism) of the existing world view, and synthesis (creation) of a revised world view including possibilities for action.

  This revised world view represents *intelligence* (in a military sense).

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[5] Note that "knowledge" in this construction has a much more specific meaning than Popper's generic use of the term.

- *Decision* selects amongst possible actions generated by the orientation, tentative solutions or action(s) to try. Choice is governed and informed by
  - *wisdom* based on experience gained from previous OODA cycles, and
  - the synthesis (creation) of new possibilities or hypotheses (tentative solutions) to try.
- *Action* puts tests decisions against the world. The loop begins to repeat as the entity observes the results of its action.

Similar cyclic learning processes have been proposed, e.g., "double-loop learning" (Agyris and Schon 1978; Blackman et al. 2004), "SECI spiral" (Nonaka and Takeuchi 1995), "knowledge life cycle" (McElroy 2000) and "decision-execution" cycle (Firestone and McElroy 2003). McElroy, Firestone and Blackman et al. specifically base their concepts on Popper. However we prefer the generality of Boyd's OODA loop and focus on learning, adaptation and survival in the very pragmatic competitive environments of warfare. An entity able to iterate an OODA cycle faster and more effectively than its competitors can change the world to its own strategic benefit before its competitors can fully orient and act. Competitors responding to a world that has already been changed by an entity with faster/more effective OODA processes will be acting on a different world than it observed, and hence will make more errors in its actions (Boyd 1976-1996; Coombe 1999).

Popper's (1972) second major insight is an ontological framework that divides existence into three ontological domains or "worlds", in which the origins, nature and growth of knowledge can be understood (see Popper 1994, Niiniluoto 1999; Hall 2005):

- *World 1 ("W1") is dynamic physical reality and everything in it.*
- *World 2 ("W2") is the domain of embodied behavior, mental states and processes within minds, dispositional and tacit knowledge*. From Popper's (1972) extended discussions of the three worlds and their interrelationships, we understand that W2 can be taken to encompass the active processes and results of cognition in individual entities. Cognition produces embodied or "dispositional" knowledge. By extension, W2 can be broadly interpreted to include the embodiment of all kinds cybernetically self-defined and self-regulated dynamic processes (Maturana 1970; Maturana & Varela 1980; Lyon 2004). In other words, W2 contains the semantic significance or meaning of cognitive processes and their results while the physical dynamics of the matter involved in the processes remains always in W1.
- *World 3 ("W3"). The domain of persistently codified or linguistically expressed knowledge, where encoded content can exist objectively, independent from a knowing entity*. We disagree with Niiniluoto (1999: p. 23) that W3 is limited to the "products of human social action". We read Popper to say that W3 comprises the products of all kinds of cognition. Popper clearly defined W3 to include knowledge in the objective sense, which includes "the world of the logical *contents* of books, libraries, computer memories, and suchlike" (1972: p. 74) and "our theories, conjectures, guesses (and, if we like, the logical content of our genetic code)" (1972: p. 73), while the physical structure of the codified content remains always in W1.

Putting the foregoing ideas together, W1 encompasses everything. It is the dynamic reality that exists independently of observation, knowing and knowledge. *Observation*, *meaning* and *knowledge* emerge dynamically to form W2 as a consequence of universal laws governing physical processes in W1, as W1 processes impact dynamic entities able to distinguish themselves from the rest of the world (i.e., autopoietic entities).

- *Observation* is a dynamic change ("*perturbation*") propagated within the autopoietic system resulting from an interaction with the world.
- *Meaning* is a consequence of the observation induced change in the constitution of the autopoietic system, e.g., where the observation triggers a cascade of further changes that are eventually captured into a stable attractor basin (Kauffman 1993).
- *Knowledge* (in one sense) is the persistent effect of a history of observations, meaning and dispositions to act as embodied in successfully surviving autopoietic systems, i.e., solutions to problems.

Here, as pointed out by Hall 2005, we also wish to emphasize the connections between autopoiesis and Popper's ideas above to an already developing biophysical theory of information, knowledge and (genetic) codification (Schroedinger 1944; Pattee 1965, 1972, 1995, 1995a, 1997, 2000, 2001; Hoffmeyer & Emmeche 1991; Rocha 1997, 1998, 2000; Rocha & Hordijk 2004; Lemke 2000; Collier 2003). These authors discuss physical issues relating to the emergence of information and knowledge (in the broad sense) as solutions to problems of existence that are embodied and enacted in living and evolving entities (i.e., those having properties of "circular closure" or autopoiesis). Cognition and knowledge can only be a phenomenon of "living" systems (Pattee, 1982, 1995; Lyon 2004) In such systems, knowledge is formally separate from the entropically driven physical processes that generate knowledge or are controlled by it. Pattee uses the concept of an "epistemic cut" to differentiate *what is* from *knowing about.*

What knowledge means organismically and organizationally remains to be defined below.

4. Emergence of autopoiesis and knowledge

A series of illustrations may make the emergent natures of autopoiesis and knowledge in a physical world clearer.

As noted in Section 2, complex dynamic systems are dissipative, formed by cyclically coupled processes serving to transform and transport matter and energy from environmental sources of higher potential (high exergy) to environmental sinks at lower potential. Unless the fluxes are so great they force the system into chaos and disintegration (e.g., as the result of a "short circuit" - McKelvey 2002, 2004), the transport processes are necessarily cyclical (Salthe 2004). So long as the net result of the summation of all system processes conducting the flux is to increase entropy, coupled processes within the complex system can be driven to lower entropy (higher exergy). The growth and development of living cells driven by the cyclical metabolic transformation of sugars and oxygen into carbon dioxide and water + heat is an example of this process in biological systems (e.g., see discussion of intermediary metabolism in Nelson and Cox (2005) or any other modern biochemistry text).

Figure 4 depicts four stages in the historical evolution of survival knowledge in a system (or holon), where the entity is represented as a stabilized eddy in the turbulent and dissipative flux from high exergy sources (resources) to high entropy sinks (waste, heat and disorder). The entire physical dynamic process represented here exists in Popper's W1.

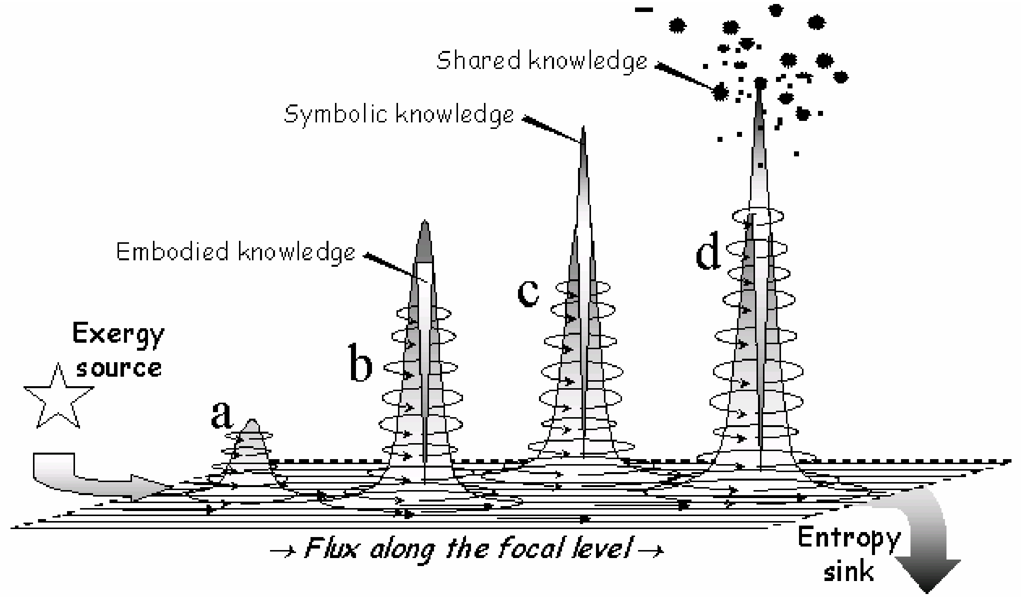

Figure 4. Stages in the evolution of autopoietic knowledge. **a**. A stabilised eddy in a turbulent flux from source to sink. **b.** A surviving autopoietic system or holon - i.e., one where the structure of the system retains the dispositional capacity to produce and reproduce itself. **c.** An evolving autopoietic holon where the solutions to problems of survival have been codified in persistent form able to be recalled in appropriate circumstances. **d.** In individual in a "biological species" able to exchange and share codified knowledge susceptible to intersubjective criticism. [Note: an animated version of this graphic is available on http://www.hotkey.net.au/~bill.hall/TheElephant2(internet).pps]

(**a**), is a cyclic "eddy" being temporarily maintained by external circumstances of its environment that is dissipating exergy of the flux. Such eddies form spontaneously and frequently (Salthe 2004). (**b**) represents the survival of systems that have accumulated a baseline of coupled processes and attractors (Kauffman 1993) embodied in the system that enable it to maintain its identity and to self-produce and self-regulate its components and processes as required to self-maintain its autopoietic capacity. This is dispositional or W2 knowledge (Popper 1972) in the form of the cybernetic relationships. In (**c**), subsystems of genetic or linguistic codification, transcription and translation have evolved between effect, symbol and action to inertly and persistently store survival knowledge that can be recalled as appropriate and reconstituted into the entity's structure and actions (Pattee 1997, 2001; Rocha 1998, 2000; Rocha and Hordijk 2004). The establishment of such persistent forms of knowledge begins to populate Popper's W3. In (**d**), persistently codified knowledge can be replicated, shared and exchanged among physically separate autopoietic entities through the external environment. Processes include transformation and transduction (transfer of DNA molecules between bacteria), eukaryote conjugation and sexual reproduction, writing and reading, etc.

How knowledge emerges and co-evolved with autopoiesis is illustrated in Figure 5.

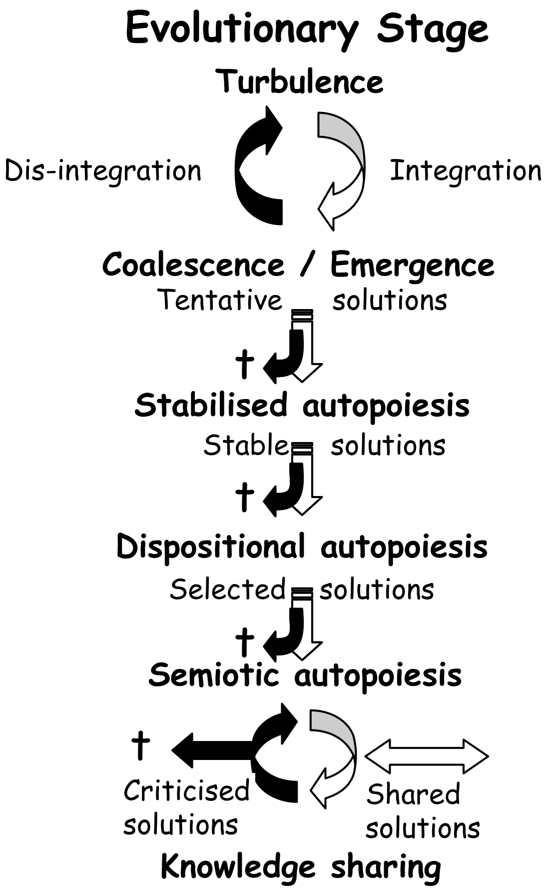

Figure 5. Stages in the coevolution of autopoiesis and autopoietic knowledge. Black arrows directed towards the cross represent the elimination of erroneous solutions. Clear arrows represent solutions that have survived problems of life.

- *Autopoietic evolution begins with turbulence in dissipative fluxes from sources to sinks*. Complex recursive systems repeatedly form, dissipate and reform as eddies or vortexes in the flux of energy and materials from sources to sinks. Self-regulatory/self-productive (autocatalytic) activities that persist for a time before disintegrating produce components whose individual histories "precondition" them to form autopoietic systems. Coalescent systems have no past. However, if an emergent eddy has any autocatalytic/autopoietic capacity, while it survives as a holon it will produce more components of kinds that have the tested capacity to participate in the formation of autopoietic 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 produced and tested in such temporarily 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. This may be regarded to represent a form of knowledge held at the subsystem level. Rasmussen et al. (2003), Pross (2005) and Pross and Khodorkovsky (2004) provide examples of what this phenomenon may look like at the chemical level.

- *Stabilized autopoietic systems are those whose tentative solutions enable them to persist indefinitely, thereby establishing a lineage through historic time*. At this stage survival knowledge is embodied in the fitness of the component subsystems and the successful self-regulation and self-production of processes within the holon. Those holons that fail to solve new problems dis-integrate and lose the historical successes of their embodied solutions.
- *Dispositional autopoiesis refers to the state where autopoietic lineages perpetuate historically successful solutions for survival into their self-produced processes and material structure to form dispositional or tacit knowledge (W2)*. Competition is inevitable among such holonic systems for limiting environmental resources of exergy and material components required for self-production, growth and replication. The consequence of error elimination is that survival knowledge will grow in those lineages that survive their problems of life.
- *Semiotic autopoiesis evolves when holonic lineages are driven to evolve means to codify and store their tested survival solutions in comparatively inert persistent form for later retrieval and enactment when relevant to particular problems of life (W3).* (Pattee (1997, 2001), Rocha (1998, 2000), and Rocha and Hordijk (2004) discuss biophysical implications of coding that segregates knowledge from system dynamics. 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 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 (Watson et al. 2004) represent such knowledge transfer and sharing. Where linguistically expressed objects are shared, they can be intersubjectively criticized.

Knowledge in its most general definition represents solutions to problems of life. Another view of how knowledge emerges and works in autopoietic systems in the framework of Popper's (1972) three worlds is shown in Figure 6.

As noted above, two fundamentally different kinds of knowledge need to be understood and distinguished:

- *Embodied or dispositional knowledge*. When an autopoietic lineage achieves sufficient stability to begin accumulating dispositional knowledge, this is embodied in cybernetic relationships of the holon's component subsystems and the processes of their interactions. In humans this corresponds to tacit knowledge (Polanyi 1958, 1966). Embodied knowledge is accumulated into the cybernetic infrastructure of the holon as the result of successful responses to observations and "measurements" of the world. The knowledge embodied in the holonic substructure constrains, regulates and controls the relationships and activities of the subsystems.

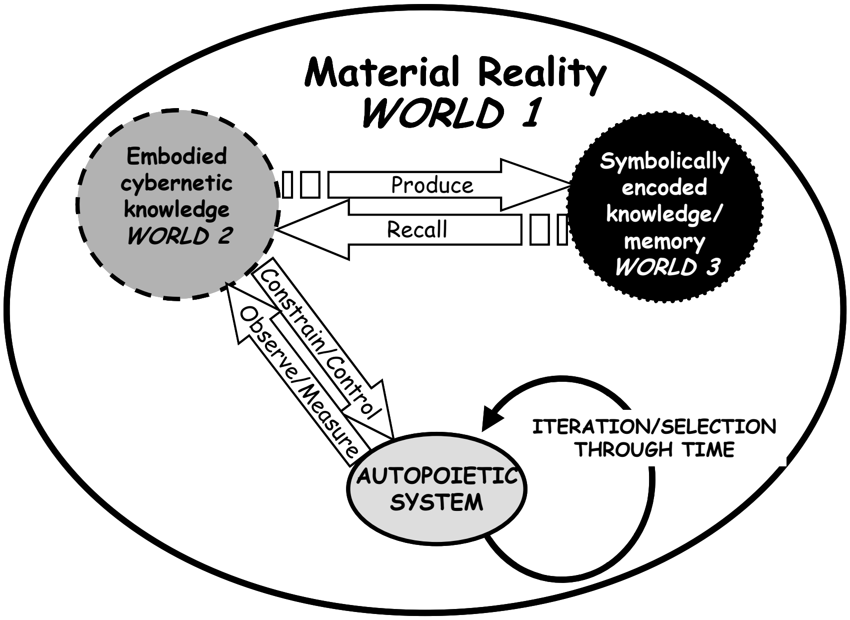

Figure 6. The autopoietic emergence of knowledge in the domains of Popper's three worlds (from Hall 2005).

- *Persistent, symbolically encoded knowledge* emerges with the evolution of mutually supporting capabilities to
    - *abstract and encode* results of successful solutions to problems of life in metabolically inactive persistent forms,
    - *propagate and store* objects of experience in W3, and
    - *trigger, retrieve from W3, transcribe and enact* appropriate objects containing relevant solutions in response to problems of life.

Such knowledge is produced into W3 storage objects from W2 by the embodied cybernetic processes of maintaining the autopoietic holon. The existence of this stored knowledge is demonstrated when it is triggered and recalled back into W2 to guide/regulate/control cybernetic processes acting on the real world.

Figure 7 illustrates the process of cybernetic cognition as observations impinging on an autopoietic entity are classified and given meaning for conversion into knowledge.

Some initial definitions will help to clarify the explanation:

- *Perturbation*: a change in the external environment that impacts the autopoietic system.
- *Observation (datum)*: Initial change induced within the autopoietic system by a perturbation.
- *Classification*: Process by which an induced change results in the system settling into one of alternative attractor basins on a landscape of potential gradients (Rocha & Hordijk 2005).

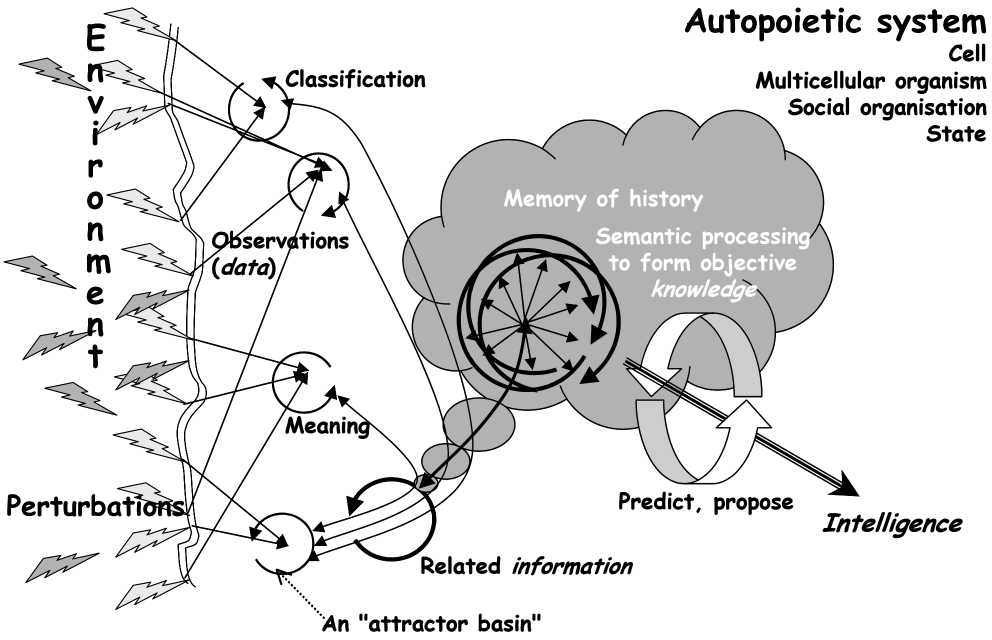

Figure 7. The integration and assembly of knowedge from data in an autopoietic holon. [Note: an animated version of this graphic is available on http://www.hotkey.net.au/~bill.hall/TheElephant2(internet).pps]

- *Meaning*: The net result within the holon due to the initial propagation and classification of an observation
- The remaining terms derive from Coombe's information transformation hierarchy (Coombe 1996, 1999), discussed earlier.

The process begins with environmental perturbations (the lightning bolt symbols) from the impinging on the system's boundary. Some have no lasting effect. Others (lighter colored) are absorbed, causing local cascades of changes within the holon's fabric. Depending on the nature of each cascade, experience embodied in the holon's cybernetic structure causes local cascades to relax into particular attractor basins that classify and give meaning to data from the perturbations (Rocha & Hordijk 2005). Once the data is assigned meanings, these meanings can be syntactically related for processing against the memory of history to place the information in a semantic framework within the existing body of knowledge and experience. Where a symbolic capability exists, the semantically signified knowledge may be codified for analysis and the synthesis of intelligence.

Figure 8 illustrates propagation through an autopoietic system of the kinds of interactive processes necessary to complete an entire OODA loop from observation of a perturbation in the environment, through orientation and decision, to the production of an action causing an effect on the environment. Note that the process depends on capabilities embodied in the system in the form of processing paradigms.

- *Observation*: Starting from the upper left corner, a perturbation impacts some aspect of the holon's structure, where it is transduced into a cascade of internal changes.

These relax into an attractor basin that classifies and links the event into a syntactically meaningful observation (Rocha & Hordijk 2005).

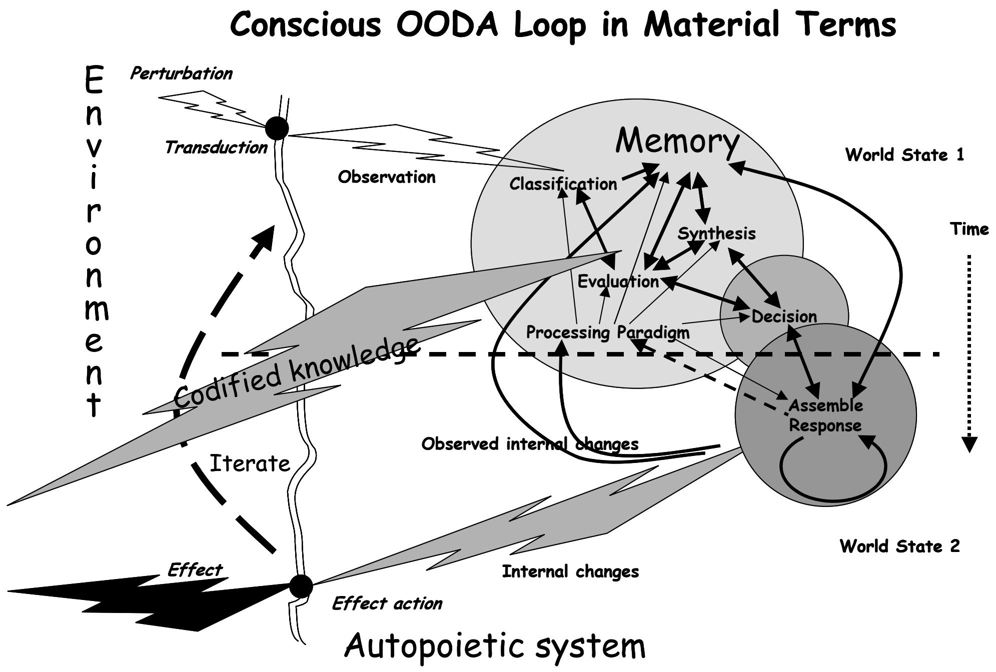

Figure 8. Graphical representation of an OODA cycle (Boyd 1996) in autopoietic cognition. [Note: an animated version of this graphic is available on http://www.hotkey.net.au/~bill.hall/TheElephant2(internet).pps]

- *Orientation*: Observations interact with memories of past observations, signifying them semantically for processing and synthesis to construct an updated worldview. Changes in that worldview are evaluated to determine if a response is needed. Aspects of the worldview and learning from observation of changes from prior worldviews may be codified for storage, criticism and sharing.
- *Decision*: Various tentative solutions are constructed using what is known from the current worldview and prior experience, and then evaluated to select and plan a course of action.
- *Action*: A response is assembled based on the selected solution and assembled knowledge and intelligence and the decided action is enacted via a cascade of internal changes that are transduced into an effect on the external environment.
- *Iteration*: Results of the action are observed to update the worldview and flag as errors concepts, decisions, actions etc. that are dissonant or do not accord with the updated worldview and understanding of reality.

5. Multiple Levels of Autopoiesis in a Hierarchically Complex World

Autopoiesis was originally described as a set of criteria applying to the cellular level of organization, where subsystem components of the autopoietic holon consisted of molecules and macromolecules. Some argue that the concept was developed for molecularly based entities at the cellular level, and doubt that social organizations can be construed to meet requirements for autopoiesis (Maturana 2002; Mingers 2003; Urrestarazu 2004). We accept that the discussion here to now is most obviously applicable to cellular entities based on molecular components. However, we argue here that autopoiesis may emerge at several focal levels in a hierarchically complex world.

The issue in analyzing candidate cases at levels of organizational hierarchy above cells is to understand the level of focus and its interactions with the next higher and lower levels in the complex system hierarchy. The lower or sub-system level consists of the subsystems and components contributing to the formation of a holon at the focal level (Salthe 1985, 1993, 2004). Whether the holon is autopoietic or not is determined only by laws governing the activities and interactions of the objects and components existing *in the subsystem level* of the holonic triad, i.e., this next lower level need not be the molecular layer. Similarly, the holon's emergence and evolutionary history will be determined by constraints, boundary conditions and situational history imposed by its immediate external environment, i.e., *the next higher level* in the systems hierarchy. For example, the environment of a living cell within a multicellular organism is the internal, homeostatically controlled environment within the body of the multicellular organism. This organismic supersystem mitigates many problems of life while it also imposes many control and boundary conditions on what the cell can do in its trajectory through historical time. Nevertheless the cell is autopoietic.

Biologists have long debated where natural selection can operate, e.g., at genetic (molecular), organismic, population or species levels. For example, Grantham (1995) and Gould (2002)[6] have considered whether natural selection can operate on higher-level entities such as populations ("groups") or biological species. Gould's hierarchical theory of natural selection (2002: 595-744) is founded on the concept of an evolutionary individual (after Janzen 1977). In Gould's terms "...natural selection works by a struggle (actual or metaphorical) among individuals for personal reproductive success... [S]election occurs when properties of a relevant individual interact with the environment in a causal way to influence the relative representation of whatever the individual contributes to the hereditary make-up of future generations." (p. 579). Gould's properties for recognizing evolutionary individuals at a particular focal level (pp. 608 ff.) include reproduction, inheritance, variation, and interaction (with the environment and like entities at the focal level).

To us, the most important consideration of Gould's discussion of hierarchical selection is his recognition of the particular importance to situate analysis of evolutionary phenomena at a particular focal level in the complex hierarchy. To determine whether a discriminable entity at a particular focal level qualifies as an evolutionary individual, the relevant subsystem and environment levels must be carefully defined *for completing the triad for that particular focal level*. From this analysis, Gould concluded that "persons" within populations, populations within species, and species within clades all represented evolutionary individuals available to be shaped through natural selection. Although Gould

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[6] We note that several aspects of Gould's hierarchical theory of natural selection, including the concept of a focal level seem to follow Salthe's thinking, without any attribution.

seemed unaware of the concept of autopoiesis, it also follows (to be elaborated elsewhere) that evolutionary individuals must also be autopoietic entities.

We next apply this kind of analysis to human economic organizations.

6. Are Organizations Autopoietic?

Some authors consider that human social organizations might be considered to be autopoietic e.g., Kay 2001; Kay & Cecez-Kecmanovic 2002; Brocklesby and Campbell-Hunt. 2004)[7]. However, none of these analyses are grounded in the kind of hierarchical analysis presented here.

We follow Gould's (2002) approach for deciding the status of an evolutionary individual that requires analysis to be limited levels of the complex hierarchy immediately above and immediately below the focal level of interest. Our interest in this case is the level of human economic organizations (e.g., independent companies or firms for the simplest case). The subsystem/component level is comprised of individual people associated with the organization from time to time, together with premises, plant, equipment, and vehicles etc. the organization controls. Interactions of elements in the subsystem/component level follow generic laws and regularities appropriate to that level. These enable emergence of complex system phenomena at the focal level. The supersystem/environment level is determined by higher-level organizations such as governments and economies. These establish the boundaries and constraints within which focal level systems have to operate (Salthe 2004).

In this situated analysis, 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:

- *Self-identifiably bounded* People know what organisations they belong to. For the benefit of other individuals and organisations, members are variously tagged with ID badges, bear membership cards, wear uniforms displaying the company logo, etc.
- *Identifiable components within the boundary.* 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.
- *Mechanistic.* Individuals receive rewards and benefits to belong, and are involved in processes, routines, procedures etc. that the organization needs for its survival.

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[7] Luhman (1984/1995) and a significant group of Postmodernist followers, have proposed a form of social "autopoiesis" based on information relationships between individuals. Although referencing Maturana and Varela, the concepts of Luhman's school are so different from the biophysical approach we take here, that to review them would greatly increase the complexity of our paper and contribute nothing to our conclusions.

- *System boundaries internally determined*. Rules of association, voluntary allegiance to organizational goals, etc. determined within the organization itself determine what people and property, etc. belong to the organization.
- *System intrinsically produces own components*. 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.
- *Self-produced components are necessary and sufficient to produce the system*. Most organisations outlive the association of particular individuals and are readily able to replace plant and equipment as it wears out.

If these assertions do represent properties of many organizations, then at least those organizations having this set of properties must evolve through time as evolutionary individuals and generate knowledge in their own rights that is capable of being managed.

Figure 9 illustrates the complex systems environment of an autopoietic human economic organization. High exergy inputs include income, energy (e.g., fuel, electricity, etc. used to drive physical transport, production machinery, computers, etc.). Sinks include high entropy heat and waste, expenses, etc. The primary fluxes of cash flow and the dissipation of exergy drive other processes such as the acquisition of materials and the production of products, and the transformations of observations of the world into actions on the world. Recruitment, induction, training and retention of staff to make them components of the organization is a necessary continuing process to replace staff leaving the organization.

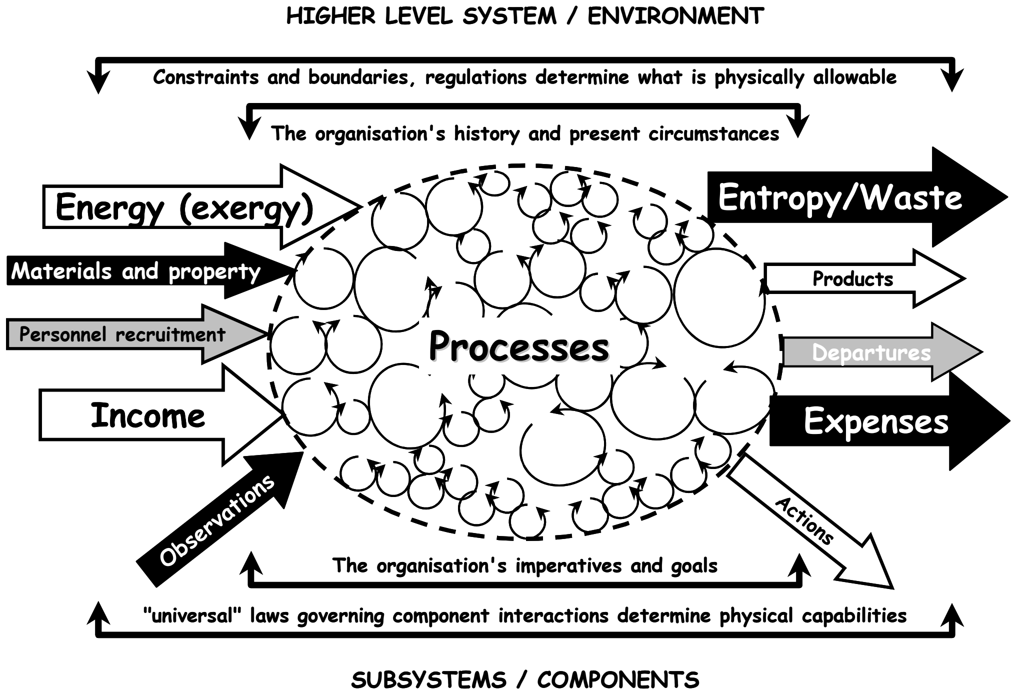

Figure 9. An autopoietic entity as a complex self-producing system of interconnected processes driven by the transport of fluxes from higher potential sources to lower potential sinks. Intersecting circles represent coupled processes.

The intersecting circles within the boundary represent the cybernetic fabric of intersecting and fundamentally cyclical processes regulating, sustaining and producing the autopoietic organization. Dissipative energy fluxes ultimately drive all processes within the holonic organization (1999, 2001, 2002, 2004). Conveniently, many energy fluxes can be abstracted in the form of cash flow that can be readily brought to account. For example, personnel are paid cash, which they use to sustain their own energy requirements (e.g., for food, shelter, heating, etc.). Similarly, plant and equipment are procured for cash, which again ultimately represents the cost of the energy and materials expended by the suppliers to design, produce and distribute the equipment. Products are sold for cash, representing cost of materials, labor, etc., expended within the organization to fabricate them.

What the organization can do is determined by the competencies of its individual members, plant and equipment and the underlying laws governing their interactions as directed by imperatives and goals deriving from organizational needs and requirements based on these governing principles (Nelson and Winter 1982). What the organization may actually do is constrained by its immediate circumstances as determined by past history and overall constraints and boundary conditions determined by the environment it finds itself in.

7. Case Studies in the Popperian Autopoietic Framework

To this point, development and discussion of the biological framework for knowledge management has been purely theoretical. Does this theory help us understand real world phenomena relating to the management of knowledge in organizations? We briefly review three cases relating to a large engineering project management organization (EPMO) where we are using the Popperian autopoietic framework to inform our work.

Practical knowledge management in a corporate environment involves a balance of three major legs: people, process and infrastructure to support knowledge content (AS 5073-2003). The following cases represent each of the three legs.

7.1 Fleet Lifecycle Knowledge Management (Infrastructure)

One of us is by training an evolutionary biologist interested in the origins and early evolution of life (Hall 1966); genetics, systematics and the formation of new species (Hall 1973); and Popperian epistemology (Hall 1983). He has now been a member of EPMO for more than 15 years, primarily involved with analyzing and designing content and knowledge authoring and management systems for assembling and delivering technical data and documentation required to build and sustain fleets of warships and vehicles (Hall 2001, 2001a, 2003; Hall et al. 2001; Sykes and Hall 2003) for lifecycles measured in decades. In the above projects, Hall viewed the organization via a paradigm that treated the organization as a biological entity with organizational needs transcending those of its human members. James Martin's (1996) biologically framed book Cybercorp accurately described Hall's initial understanding of how such an organization worked. A senior executive in EPMO also widely recommended Martin's book, apparently because he also believed the book described the organization.

As increasingly complex and important documentation and knowledge management projects were tackled, first the ideas of Popperian epistemology (Hall 2003), then Coombe's transformational hierarchy of knowledge terms and Boyd's OODA loop concept, and finally autopoiesis (Hall 2003a) were explicitly implemented as design considerations in building practical solutions for real problems faced by the organization.

A full mapping of the theoretical framework recounted here is mapped onto the practical requirements for managing fleets of warships and vehicles in Hall et al. (draft).

7.2 Methodology for Improving Knowledge Based Business Processes (Processes)

Dalmaris et al (in press) developed a framework for improving knowledge-intensive business processes as part of his PhD research. The framework consists of a Popperian epistemology (used as the foundation), a business process ontology (used to accurately describe and analyze business processes), and an improvement methodology. The framework was refined in an evolutionary approach based on a sequential analysis of three separate cases involving separate organizations. The last of the organizations was EPMO.

Dalmaris's research applied the Popperian framework in three ways:

- Popper's (1972) three worlds epistemology was used as the basis for developing an ontology (the second component of the framework)
- The improvement methodology (the third component of the framework) as applied in practice includes Popperian error reduction to identify and eliminate business process errors. The methodology includes three steps:
  - *Audit*, where the present business process is analyzed and understood “as is”.
  - *Analysis*, where Popperian criticism is applied to identify potential areas for improvement.
  - *Design*, where tentative solutions are produced and criticized to address the issues of the identified potential improvement areas. This effectively produces an “as could” configuration of the business process.
- A Popperian OODA approach (Boyd 1976-1996) was followed to improve the analytical theory and research methodology itself by recursively eliminating errors of three types:
  - *Errors of theoretical foundation*: These are errors relating to epistemology, and its ability to provide suitable definitions to the fundamental questions related to this research, such as “what is knowledge”.
  - *Errors of process representation*: These are errors relating to the representation of a business process as an instance of a business process ontology.
  - *Errors of improvement methodology*: These are errors relating to the application of the improvement framework on a business process.

The Popperian methodological approach used to develop the framework from the analysis of business processes in three quite different organizations was especially important, as it allowed for the systematic detection and correction of many problems, especially in the early stages of developing the methodology. As most problems were of either ontological or technical nature, their early detection and correction significantly reduced the total research time and improved its overall quality.

Further, the Popperian method was incorporated in the improvement methodology itself. The audit, analysis and design steps reflect an integration of Popper's criticism through trial and error and the OODA loop. The audit step combines observation and orientation, while the analysis step represents decision, and the design step represents action.

The result (Dalmaris et al in press), is a clearly articulated improvement methodology that is applicable to many business process, as the so far completed field testing has confirmed.

7.3 Supporting the emergence and sustainment of communities of practice

It is difficult for organizations to effectively manage personal knowledge so it can be mobilized, shared, and rewarded to benefit the organization. The difficulties are compounded in large organizations where people with potentially valuable knowledge are unknown to one another and dispersed geographically across time zones. Issues that are potentially amenable to knowledge management solutions include identifying, indexing and codifying personal knowledge; and the cultural issues of discovery, mutual trust and sharing at the personal level.

Nousala is developing a methodology as part of her PhD research to address problems managing personal knowledge in distributed technology oriented enterprises. One of Nousala's case organizations, EPMO exists in a fiercely competitive environment, where its primary imperatives are to qualify and win more contracts (increase revenue), perform better on contracts won (increase ROI), manage and mitigate risks, and to satisfy customers to generate return business. Other imperatives include providing a safe, healthy, and rewarding work environment for its employees; complying with governmental regulations at all levels, and responding to community and environmental standards and expectations. In a decade and a half, the enterprise has grown from a company centered on a single large project, to a large and diverse organization with multiple business units, where divisions in the largest business units are distributed across several time zones and countries.

Again, Nousala's thesis has used a Popperian OODA learning strategy to understand the factors facilitating the emergence of effective communities of interest and practice, in a sequence of four case studies in different kinds of knowledge based organizations (Nousala, 2003; Nousala and John, 2004; Nousala et al. Submitted2), the last, as detailed in Nousala et al. (Submitted), is EPMO.

The case study for the project engineering organization involved a methodological approach adopted specifically for project engineering organizations. This approach was adopted due to project oriented organizations being hierarchical by nature, in contrast to knowledge sharing through communities of practice which rely on horizontal tacit knowledge networks (Nousala and John 2004). Personal knowledge needs to be shared across the organization in order to be sustainable.

Communities of practice (CoP) are entities made up of individuals who offer support through an intersection of commonality, where unifying cause or actions holds the interactions of individuals together.

The CoP concept has been identified within the current knowledge management literature as a fundamental aspect of human complex organizational systems behavior. To us some such communities appear to have some or all of the properties to be deemed as an autopoietic entity in their own right according to Varela et al. (1974). The CoPs analyzed in this research are treated as autopoietic components or holons within the larger supersystem comprising the project oriented organization.

Snowden (2000) observed that asking people for narratives or to tell "stories" about their work seemed to elicit or expose the emergent common messages or points which in time, would reveal some sort of discernable pattern. He also argues that the human knowledge is a contextual thing, shaped by circumstance. Snowden goes on to discuss and describe knowledge disclosure through narrative patterns as a means by which to create circumstances that trigger people into knowing what they know, when they need to know it.

Managing knowledge in this way through context requires a fundamental recognition that the a supportive ecology for individuals in CoPs must not only be recognized but actively supported to allow the CoP concerned to share necessary knowledge between individuals, groups and organizations.

To retain the contextual aspect of the knowledge that needs to be shared the methodological approach required a level flexibility to support varied and in-depth experiences of individual members in context. The method involved semi-structured interviews support by a mind mapping process. The method focused on the initial “starting point” being an individual member, who was linked to a community or working group.

The case study investigated specific emergent factors of CoPs and working groups. This included individuals discussing similar types of successful ideas and working experiences as well as common barriers. It was important to gain an understand of what specific emergent aspects would help to sustain such communities or working groups that were specifically beneficial within project oriented organization. This case study initially focused on the following levels in the complex systems hierarchy:

- individuals within a COP as component/subsystem elements in the CoP, and,
- interactions among the individual within the CoP processes in relationship to the area practice and time required.

For each organization or entity, time applies differently to relevant knowledge levels. Applying the appropriate time line or framework would be difficult without the understanding of the knowledge levels involved. This then adds to another layer to be aware of when considering different groups interested in the communication or exchange of their knowledge.

To support horizontal knowledge sharing in hierarchical project engineering organizations, tacit knowledge networks need to be based on well-structured ontology.

Nousala's study also reveled that certain key individuals termed “human attractors” who were important parts of, or helped communities or groups to coalesce or emerge. As such, human attractors were instrumental for the development of expert communities of interest (ECOI). These ECOI were communities that occurred within the project engineering organization, due to the specific expertise required within these project environments. Human attractors were also precursors to the more general communities of interest (COI). Both of these communities of interest were precursors to the CoP. At the ECOI and COI levels, if appropriate constraints (for example, peer review) are applied the communities of interest have an opportunity to develop into sustainable CoPs.

8. Conclusions

The paper presents a theoretical framework for understanding the nature of knowledge in organizations, and provides some examples of where it has been applied in practical case studies. Although the scope of the present format only allows scope for an overview of the framework, it does appear to inform many aspects of organizational theory and the management of knowledge within organizations.

Students using the framework to guide practical case-study research have also found that it has given their work significantly greater clarity than might have otherwise been achieved.

Most interestingly, studies by Nousala et al. (Submitted), as summarized above, strongly suggest that communities of practice represent borderline and emerging autopoietic entities at a focal level within large organizations or across organizations in the larger community environment between the subsystems level of individual people, and the supersystems level of whole organizations. As such, because they are particularly amenable to study within the lifetime of an investigator, they may provide an ideal class of objects for studying general factors surrounding the origin of life at any level of complexity where life can be said to exist.

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BIBLIOGRAPHY

Anonymous Undated. The Personal Papers of Colonel John R. Boyd (USAF): Part II. War, Chaos and Business - http://www.belisarius.com/modern_business_strategy/boyd/boyd_papers.htm

AS 5073(Int)-2003. Knowledge Management. Australian Standard AS 5073(Int)-2003. SAI Global - http://www.standards.com.au/catalogue/script/Details.asp?DocN=AS110152272410

Blackman, D., Connelly, J., Henderson, S. 2004. Does double loop learning create reliable knowledge? Learning Organization 11(1): 11-27.

Boyd, J.R. 1976–1996. Unpublished briefings under the name "A Discourse on winning and losing": Introduction (1996), Patterns of conflict (1986), Organic design for command and control (1987), Strategic game of ? and ? (1987), Destruction and creation (1976), and The essence of winning and Losing (1996) available via Defence and the National Interest - http://www.d-n-i.net/second_level/boyd_military.htm.

Brocklesby, J., & Campbell-Hunt, C. 2004. The evolution of competitive capability in exemplar firms - A cognition and complex systems perspective. International Journal of Organisational Transformation and Social Change, 1(2-3), 143-162.

Campbell, D.T. 1960. Blind variation and selective retention in creative thought as in other knowledge processes. Psychological Review 67:380-400.

Chaisson, E.J. 2001. Cosmic Evolution: The Rise of Complexity in Nature; Harvard University Press: Cambridge.

Collier, J. 2003. Hierarchical dynamical information systems with a focus on biology. Entropy 5:100-124. - http://www.mdpi.org/entropy/papers/e5020100.pdf

Coombe, I., 1996. Army Information Management Manual (Ver 2.0, 2 May 1996). Australian Army, Canberra. [Although not credited, Coombe was the consultant who assembled this version]

Coombe, I., 1999. Decisions and power in the information age (WIKID power): 1994–1999 http://web.archive.org/web/20010302160925/http://www.eclectic.au.com/speclty/im/iml.htm

Dalmaris, P., Tsui, E., Hall, W., Smith, B. In Press.. A Framework for the improvement of knowledge-intensive business processes. Business Process Management Journal forthcoming.

Davies, P. 2004. Emergent Biological Principles and the Computational Properties of the Universe" Complexity 10 (2), 1 (2004) - http://aca.mq.edu.au/PaulDavies/publications/papers/complexity_paper.pdf.

de Zeeuw, G., 2001. Constructivism: a `next' area of scientific development? Foundations of Science 6:77-98.

Emmeche C. 1997. Defining life, explaining emergence. - http://www.nbi.dk/~emmeche/cePubl/97e.defLife.v3f.html

Emmeche, C., Koppe, S., Stjernfelt, F. 1997. Explaining emergence - towards an ontology of levels. Journal for General Philosophy of Science 28: 83-119. - http://www.nbi.dk/~emmeche/coPubl/97e.EKS/emerg.html

Firestone, J.M., McElroy, M.W. 2003. The Open Enterprise: Building Business Architectures for Openness and Sustainable Innovation. KMCI Publications Group, Hartland Four Corners, VT. - http://www.dkms.com/oemarketing.htm

Firestone, J.M., McElroy, M.W. 2003a. Key Issues in the New Knowledge Management. KMCI Publications Group, Hartland Four Corners, VT

Giampietro, M., Mayumi, K., Pastore, G. 1999. Energy analyses as a tool for sustainability: lessons from complex system theory. Annals of the New York Academy of Sciences 879:344-367,

Gould, S.J. 2002. The Structure of Evolutionary Theory. Belknap Press of Harvard University Press, Cambridge, Mass. 1433 pp.

Grantham, T.A. 1995. Hierarchical approaches to macroevolution: recent work on species selection and the "effect hypothesis". Annual Review of Ecology and Systematics 26: 301-321

Hall, W.P. 1973. Comparative population cytogenetics, speciation and evolution of the iguanid lizard genus Sceloporus. PhD Thesis, Harvard University. - http://bill-hall.afriherp.org/Hall_Thesis.htm

Hall, W.P. [1966]. Is the Plastid an Endosymbiont. 26 pp. - http://www.hotkey.net.au/~bill.hall/Endosymbiosis/Abstract.htm

Hall, W.P. 1983. Modes of speciation and evolution in the sceloporine iguanid lizards. I. Epistemology of the comparative approach and introduction to the problem. (in) A.G.J. Rhodin and K. Miyata, eds. Advances in Herpetology and Evolutionary Biology - Essays in Honor of Ernest E Williams. Museum of Comparative Zoology, Cambridge Mass. pp.643-679. - http://www.hotkey.net.au/~bill.hall/Hall1983/Hall1983.htm

Hall, W.P. 2001. Writing and Managing Maintenance Procedures for a Class of Warships: A Case for Structured Authoring and Content Management. May 2001 issue of Technical Communication, the professional journal of the Society for Technical Communication. - http://www.tenix.com/PDFLibrary/91.pdf

Hall, W.P. 2001a. How Melbourne is Contributing to the Contracts Standards Effort. Legal XML & Electronic Filing: The Australian Focus. (A joint conference between the AIJA and VSCL) - Melbourne, 25/10/2001 - http://www.aija.org.au/AIJAVSCL/AIJAVSCLtopic8.pdf

Hall, W.P. 2003. Managing Maintenance Knowledge in the Context of Large Engineering Projects - Theory and Case Study. Journal of Information and Knowledge Management, 2(2) [Correctly formatted version reprinted in 2(3):1-17]. - http://www.hotkey.net.au/~bill.hall/ManagingMaintKnowledgeinLargeEngiProjects.pdf.

Hall, W. P., 2003a. Organisational autopoiesis and knowledge management. (Presented) ISD '03 Twelfth International Conference on Information Systems Development - Methods & Tools, Theory & Practice, Melbourne, Australia, 25 - 27 August, 2003. http://www.hotkey.net.au/~bill.hall/OrgAutopoiesisAndKM(final).pdf.

Hall, W. P., 2005. Biological nature of knowledge in the learning organization. in Firestone, J.M. and McElroy, M.W. (eds), special issue Doing Knowledge Management, The Learning Organization, 12(2). http://www.hotkey.net.au/~bill.hall/TheBiologicalNatureshortrevjmf1bh3.pdf.

Hall, W.P., Jones, M., Zhou, M., Anticev, J., Zheng, J., Mo, J. & Nemes L. 2002. Document-based Knowledge Management in Global Engineering and Manufacturing Projects. Proceedings of the Globemen Plenary Meeting No. 6. 8-13 December 2002, Helsinki, Finland. - http://cic.vtt.fi/projects/globemen/book/21_hall.pdf.

Hall, W.P., Richards, G., Sarelius, K., Kilpatrick B. 2005. Organizational management of project and technical knowledge over fleet lifecycles. Draft

Henrickson, L., McKelvey B. 2002. Foundations of "new" social science: institutional legitimacy from philosophy, complexity science, postmodernism, and agent-based modeling. Proceedings of the National Academy of Sciences 99(suppl.3): 7288-7295.

Hurlbert, R.E. 1999. Chapter IX: Microbial exchange of genetic material. Micrbiology 101/102 Internet Text. Washington State University. - http://www.slic2.wsu.edu:82/hurlbert/micro101/pages/Chap9.html

Hoffmeyer, J. & Emmeche, C. 1991. Code-Duality and the Semiotics of Nature. pp. 117-166 in: Myrdene Anderson and Floyd Merrell (eds.): On Semiotic Modeling. Mouton de Gruyter, Berlin and New York, - http://www.nbi.dk/~emmeche/coPubl/91.JHCE/codedual.html

Janzen, D. 1977. What are dandelions and aphids? American Naturalist 111:586-589.

Jorgensen, S.E. 1999. Tentative fourth law of thermodynamics, applied to description of ecosystem development. Annals of the New York Academy of Sciences 879:320-343.

Kauffman, S. A., 1993. The Origins of Order: Self-Organization and Selection in Evolution. Oxford Univ. Press, New York.

Kay, J. J., 1984. Self-Organization in Living systems. PhD thesis: Systems Design Engineering, University of Waterloo, Waterloo, Ontario, Canada. - http://www.fes.uwaterloo.ca/u/jjkay/pubs/CRC/diss.pdf

Kay, R. 2001. Are organizations autopoietic? A call for new debate. Systems Research and Behavioral Science 18 (6): 461-477.

Kay, R. and Cecez-Kecmanovic, D., 2002, Towards an autopoietic perspective on knowledge management, in: ACIS 2002, Melbourne Australia, 4-6 December 2002.

Kuhn, T.S. 1970. The Structure of Scientific Revolutions, 2nd Ed., Enlarged. University of Chicago Press, Chicago, 210 pp.

Kuhn, T.S. 1983. Commensurability, comparability, communicability. in PSA 1982: Proceedings of the 1982 Biennial Meeting of the Philosophy of Science Association, Vol 2. from Kuhn (2000). The Road Since Structure. University of Chicago Press.

Lemke, J.L. 2000. Opening up closure: semiotics across scales. Annals of the New York Academy of Sciences 901:100-111.

Luhmann, N. 1995. Social Systems. [Tr. J. Bednarz and D. Baecker]. Standford University Press, Standord Calif. - first published as Soziale Systeme: Grundriss einer allgemeinen Theorie, Suhrkamp Verlag Frankfurt am Main, 1984.

Lyon, P. 2004. Autopoiesis and knowing: reflections on Maturana's biogenic explanation of cognition. Cybernetics & Human Knowing 11(4):21-46.

Magalhaes, R. 1996. Organizational Learning, Organizational Knowledge and Organizational Memory; New Proposals Towards a Unified View. Working Paper Series 20, London School of Economics, Department of Information Systems. - http://is.lse.ac.uk/wp/pdf/WP60.PDF

Magalhaes, R. 1998. Organizational Knowledge and Learning. in von Krogh, G., Roos, J. & Kleine, D., Eds. (1998). Knowing in Firms: Understanding, Managing and Measuring Knowledge. Sage Publications Ltd, London. pp. 87–122

Magalhaes, R. 1999. The organizational implementation of information systems: towards a new theory. PhD Thesis, London School of Economics. 323 pp

Martin, J. 1996. Cybercorp : The New Business Revolution. Amacom, 326 pp.

Maturana, H.R. 1970. Biology of Cognition. Biological Computer Laboratory Research Report, BCL 9.0. University of Illinois, Urbana. (as reprinted in Autopoiesis and Cognition: The realization of the Living. Reidel Publishing Co. Dordrecht. pp 5-58. - http://www.enolagaia.com/M70-80BoC.html#I

Maturana, H. 2002. Autopoiesis, structural coupling and cognition: a history of these and other notions in the biology of cognition. Cybernetics & Human Knowing 9(3-4): 5-34.

Maturana H.R. and Varela F.J. 1980. Autopoiesis: the organisation of the living. In Autopoiesis and Cognition: The Realization of the Living, Maturana H, Varela F (eds). Reidel: Dortrecht; 73-137.

Maturana H.R. and Varela F.J. 1987. The Tree of Knowledge. Shambhala: Boston, MA

McElroy, M. W. 2000. The New Knowledge Management. Knowledge and Innovation: Journal of the KMCI 1(1): 43-67. - http://www.macroinnovation.com/images/mgmnt.pdf

McKelvey, B. 1997. Quasi-natural organization science. Organization Science 8(4):352-380.

McKelvey, B. 1999. Avoiding complexity catastrophe in coevolutionary pockets: strategies for rugged landscapes. Organization Science 10: 294–321. - http://www.billmckelvey.org/docs/AVOIDING%20COMPLEXITY%20CATASTROPHE,%20Organization%20Science.%201999.pdf

McKelvey, B. 1999a. Complexity theory in organization science: seizing the promise or becoming a fad? Emergence 1(1):5-32.

McKelvey B. 1999b. Toward a Campbellian realist organization science. Baum J.A.C. & McKelvey B (eds.) Variations in Organization Science: In Honor of Donalt T. Campbell. Sage: Thousand Oaks pp. 383-411.

McKelvey, B. 2001. Energising order-creating networks of distributed intelligence: improving the corporate brain. International Journal of Innovation Management. International Journal of Innovation Management, 5:181–212 - http://www.billmckelvey.org/docs/ENERGIZING%20ORDER-CREATING%20NETWORKS...,%20Int.%20Jour.%20Innovation%20Management%202001.pdf

McKelvey, B. 2002. Emergent order in firms: complexity science vs. the entanglement trap. in Mitleton-Kelly, E. (ed.), Complex Systems and Evolutionary Perspectives of Organizations: Applications of Complexity Theory to Organizations. Elsevier, - http://www.billmckelvey.org/docs/EMERGENT%20ORDER%20IN%20FIRMS...,%20Mitleton-Kelly%20book%202002.pdf

McKelvey B. 2004. Toward a 0th law of thermodynamics: order-creation complexity dynamics from physics and biology to boieconomics. Journal of Bioeconomics 6: 65-96.

McKelvey B. & Baum J.A.C. 1999. Campbell's evolving influence on organization science. Baum J.A.C. & McKelvey B (eds.) Variations in Organization Science: In Honor of Donalt T. Campbell. Sage: Thousand Oaks pp. 383-411.

McKelvey B. (undated). Epistemology of the "new" social science. Bill McKelvey - Anderson School of Management - http://www.billmckelvey.org/newscience.html

McShea, D.W., Changizi, M.A. 2003. Three puzzles in hierarchical evolution. Integrative and Comparative Biology. Vol.43 (1):74-

Mingers, J. 2003. Can Social Systems Be Autopoietic? Bhaskar and Giddens' Social Theories. Working Paper 44. Canterbury Business School, University of Kent - http://www.kent.ac.uk/CBS/research-information/working-papers/Mingers-No-44.pdf

Morowitz, H. J., 1968. Energy Flow in Biology: Biological Organization as a Problem in Thermal Physics. Academic Press, New York

Mulligan, M.E. 1997-2005. Genetic transfer in bacteria. Biochemistry 4103: Prokaryotic Gene Regulation - Lecture Notes (see Conjugation, Conjugation (II), Bacterial transformation, and Bacteriophage transduction.. http://www.mun.ca/biochem/courses/4103/lectures.html

Nelson, D.L., Cox, M. M. 2005. Lehninger Principles of Biochemistry (Ed 4). W.H. Freeman, New York. 1100 pp.

Nelson, R.R., Winter, S.G. 1982. An Evolutionary Theory of Economic Change, Harvard University Press, Cambridge, Mass.

Nelson, R.R., Winter, S.G. 2002. Evolutionary theorizing in economics. Journal of Economic Perspectives 16(2):23–46. - http://gatton.uky.edu/faculty/castaneda/GTclass/Read/Nelson and Winter 2002.pdf

Niiniluoto, I. 1999. Critical Scientific Realism. Oxford University Press, New York. 341 pp - http://www.oxfordscholarship.com/oso/public/content/philosophy/0199251614/toc.html

Nonaka, I., Takeuchi, H. 1995. The Knowledge Creating Company. Oxford: Oxford University Press.

Nousala, S. H., 2003. Investigations into research methodologies for cultural analysis, 4th MAAOE Conference 2003 proceedings

Nousala, S. H, and John S., 2004, Tacit Knowledge Management Networks and its Implication in Organisational Prosperity, Qualcon 2004 Conference proceeding, AQQ, South Australia, Adelaide

Nousala, S., John, S. Jamsai, S. Submitted2. Tacit knowledge strategies and implementation in complex organisations: A Thai engineering company case study. The Fifth International Conference on Knowledge, Culture and Change in Organisations. Island of Rhodes, Greece 19-22 July 2005.

Nousala, S., Miles, A., Hall, W.P., Kilpatrick, B. Submitted. Team expertise access maps (TEAM) using mind mapping technologies. Knowledge Management in Asia Pacific, Auckland, 28 - 29 November, 2005. Submitted.

Pattee, H.H. 1965. Recognition of heritable order in primitive chemical systems. In: Fox, S. (ed.), The Origins of Prebiological Systems. Academic Press, New York.

Pattee, H.H. 1972. Laws, constraints, symbols, and languages. In Towards a Theoretical Biology 4, C.H. Waddington, Ed., Edinburgh Univ. Press, pp. 248-258.

Pattee, H. H. 1982. Cell psychology: An evolutionary approach to the symbol-matter problem. Cognition and Brain Theory, 5(4): 191–200.

Pattee, H.H. 1995. Evolving self-reference: matter, symbols, and semantic closure. Communication and Cognition - Artificial Intelligence, Vol. 12, Nos. 1-2, pp. 9-27, Special Issue Self-Reference in Biological and Cognitive Systems, Luis Rocha (ed.) - http://www.ws.binghamton.edu/pattee/sem_clos.html

Pattee, H. H. 1995a. Artificial life needs a real epistemology". In Advances in Artificial Life . F. Moran, A. Moreno, J. J. Morelo, and P. Chacon, eds., Springer-Verlag, Berlin, pp. 23-38 - http://www.ws.binghamton.edu/pattee/aepistem.html

Pattee, H.H. 1997. The Physics of Symbols and The Evolution of Semiotic Controls. presented at the Workshop on Control Mechanisms for Complex Systems: Issues of Measurement and Semiotic Analysis, Las Cruces, New Mexico, Dec. 8-12,1996. To be published as Santa Fe Institute Studies in the Sciences of Complexity, Proceedings Volume, Addison-Wesley, Redwood City, CA, 1997 - http://www.ws.binghamton.edu/pattee/semiotic.html

Pattee, H.H. 2000. Causation, control, and the evolution of complexity. (1997 draft) for Downward Causation edited by P. B. Anderson, P. V. Christiansen, C. Emmeche, and N. O. Finnemann. Århus: Aarhus University Press, p. 63-77 - http://www.ws.binghamton.edu/pattee/downcaus.html

Pattee, H.H. 2001. The physics of symbols: bridging the epistemic cut. Biosystems 60: 5-21.

Prigogine, I., 1955. Introduction to the Thermodynamics of Irreversible Processes. C.C. Thomas, Springfield, Illinois.

Prigogine, I. 1981. From Being to Becoming: Time and Complexity in the Physical Sciences. Freeman, New York.

Pross, A. 2005. On the emergence of biological complexity: Life as a kinetic state of matter. Origins of Life and Evolution of Biospheres 35(2):151-66.

Pross, A., Khodorkovsky, V. 2004. Extending the concept of kinetic stability: toward a paradigm for life. Journal of Physical Organic Chemistry 17: 312–316 - http://www.bgu.ac.il/chem/people/Pross/PDF-2%20(JPOC).pdf

Polanyi, M. 1958, Personal Knowledge: Towards a Post-Critical Philosophy, [Corrected Ed., 1962]. University of Chicago Press, Chicago.

Polanyi, M. 1966, The Tacit Dimension, Routledge & Kegan Paul.

Polanyi, M. 1968. Life's irreducible structure. Science 160(3834): 1308-1312.

Popper, K. R., 1959. The Logic of Scientific Discovery. Sixth Impression (Revised) First English Edition. Hutchinson, London. [First published as Logik Der Forschung Vienna: Springer; 1934].

Popper, K. R., 1963. Conjectures and Refutations: The Growth of Scientific Knowledge. [4th Ed. Revised 1972]. Routledge and Kegan Paul, London.

Popper, K.R. 1972. Objective Knowledge: An Evolutionary Approach. London, Oxford Univ. Press, 380 pp.

Popper, K.R. 1994. Knowledge and the Body-Mind Problem: In defence of interaction. (ed. M.A. Notturno). Routledge, London. 158 pp.

Radnitzky, G., Bartley, W.W., III. 1987. Evolutionary Epistemology, Rationality, and the Sociology of Knowledge, Open Court, La Salle, Illinois

Rasmussen, S., Chen, L., Nilsson, M., Abe, S. 2003. Bridging nonliving and living matter. Artificial Life 9(3):269-316. - http://frt.fy.chalmers.se/cs/people/jacobi/Publications/Articles/protolife_nilsson.pdf

Riegler, A., 2001 Towards a radical constructivist understanding of science. Foundations of Science 6:1-30.

Rocha, L.M. 1997. Evidence Sets and Contextual Genetic Algorithms: Exploring Uncertainty, Context, and Embodiment in Cognitive and Biological Systems. PhD Thesis State University of New York at Binghamton - http://informatics.indiana.edu/rocha/dissert.html

Rocha, L.M. 1998. Selected self-organization and the semiotics of evolutionary systems. in Salthe, S.N., Van de Vijver, G., Delpos, M. (eds), Evolutionary Systems: Biological and Epistemological Perspectives on Selection and Self-organization. Kluwer Academic Publishers, pp. 341-358. - http://informatics.indiana.edu/rocha/ps/ises.pdf

Rocha, L.M. 2000. Syntactic autonomy: why there is no autonomy without symbols and how self-organizing systems might evolve them. Annals of the New York Academy of Sciences 901:207-223.

Rocha, L.M., Hordijk, W. 2005. Material Representations: From the genetic code to the evolution of cellular automata. Artificial Life. - http://informatics.indiana.edu/rocha/caalife04.html

Salthe, S. 1985. Evolving Hierarchical Systems: Their Structure And Representation. Columbia University Press, New York. 343 pp.

Salthe, S. 1993. Development and Evolution: Complexity and Change in Biology. MIT Press, Cambridge, Mass. 357 pp.

Salthe, S. 2004. The spontaneous origin of new levels in a scalar hierarchy. Entropy 6:327-343. - http://www.mdpi.org/entropy/papers/e6030327.pdf

Schneider, E., 1988. Thermodynamics, information, and evolution: New perspectives on physical and biological evolution. In: Weber, B. H., Depew, D. J., Smith, J.D. (Eds), Entropy, Information, and Evolution: New Perspectives on Physical and Biological Evolution MIT Press, Boston, pp. 108-138.

Schneider, E. D., Kay, J. J., 1994. Life as a Manifestation of the Second Law of Thermodynamics. Mathematical and Computer Modelling 19:25-48. - http://www.fes.uwaterloo.ca/u/jjkay/pubs/Life_as/text.html.

Schneider, E. D., Kay, J. J., 1995. Order from Disorder: The Thermodynamics of Complexity in Biology. In: Murphy, M. P., O'Neill, L. A. J. (Eds). What is Life: The Next Fifty Years. Reflections on the Future of Biology. Cambridge: Cambridge University Press, pp. 161-172 - http://www.fes.uwaterloo.ca/u/jjkay/pubs/sch/sch.html.

Schroedinger, E., 1944. What is Life? The Physical Aspect of the Living Cell. Cambridge University Press, Cambridge.

Simon, H. A. 1962. The architecture of complexity. Proceedings of the American Philosophical Society, 106:467-482.

Snowden, D. 2000. Basics of organic knowledge management: Part one - The ASHEN model: an enabler of action. Knowledge Management 3(7) - http://www.ikmagazine.com/xq/asp/sid.0/articleid.8B4FF69B-C965-49B6-B76C-2A997D824D59/qx/display.htm; Part two - knowledge elicitation: indirect knowledge discovery. Knowledge Management 3(9) - http://www.kmmagazine.com/xq/asp/sid.0/articleid.9593F113-A20A-4A5F-9FDF-A5F1E5A12D55/qx/display.htm; Part three - Story circles and heuristic based interventions . Knowledge Management 3(10) - http://www.kmmagazine.com/xq/asp/sid.0/articleid.024D3AD4-146E-461F-8073-4905D00E520F/qx/display.htm

Sykes, M., Hall, W.P. 2003. Generating Fleet Support Knowledge from Data and Information. Australian Conference for Knowledge Management & Intelligent Decision Support ACKMIDS 2003 Melbourne, Australia, 11 and 12 December 2. - http://www.hotkey.net.au/~bill.hall/DataAndInformationInFleetKM(submitted1).pdf

Urrestarazu, H. 2004. On Boundaries of Autopoietic Systems. Journal of Autopoietic Theory. 19 May 2004 - http://autopoietic.net/boundaries.pdf

Varela F, Maturana H, Uribe R. 1974. Autopoiesis: the organization of living systems, its characterisation and a model. Biosystems 5: 187-196

von Glaserfeld, E., 1984. An introduction to radical constructivism. In: Watzlawick P. (Ed.), The Invented Reality. Norton, New York. [Originally published in Watzlawick, P (Ed.), Die Erfundene Wirklichkeit. Munich: Piper; 1981. http://srri.nsm.umass.edu/vonGlasersfeld/ onlinePapers/html/082.html.

von Glaserfeld, E., 1993. An exposition on constructivism: Why some like it radical 1993. In: Kenny, V. (Ed.), Ecology of the Mind. http://www.oikos.org/constructivism.htm.

von Glaserfeld, E., 1997. Distinguishing the Observer: An Attempt at Interpreting Maturana. In: Kenny J.F. (Ed.) Towards and Ecology of Mind - http://www.oikos.org/vonobserv.htm. [Originally published as: Die Unterscheidung des Beobachters: Versuch einer Auslegung. In: Riegas, V., Vetter, C. (Eds.) Zur Biologie der Kognition. Frankfurt: Suhrkamp, 1990:281-295].

von Glaserfeld, E., 2001. The radical constructivist view of science. Foundations of Science 6:31-43

von Krogh, G. and Roos, J. 1995. Organizational Epistemology. St Martin's Press, New York.

Watson, J.D., Baker, T.A., Bell, S.P., Gann, A., Losick, R. 2004. Molecular Biology of the Gene (Ed 5.) Benjamin Cummings.

Wu, J. 1999. Hierarchy and Scaling: extrapolating information along a scaling ladder. Canadian Journal of Remote Sensing 25(4):367-380.