New England Complex Systems Institute — International Conference on Complex Systems (ICCS 2007)
System Category: Human Social and Economic Systems

How bio-dynamics inform design process innovation
harnessing principles from complex adaptive systems

Zann Gill
DE•SYN Lab, PO Box 4001
Los Altos, CA 94024, USA
http://desyn.com
phone: 650–292–0751
e-mail: zanngill@desyn.com

DRAFT

ABSTRACT

The research community has focused on technical analyses for a range of distributed network problems, placing less emphasis on the challenge at which Nature excels — design synthesis. Whereas biomimetics copies Nature's evolutionary "products," we can also learn from Nature's "processes" about how evolution produces exquisitely adapted novelty that traditional engineering design would fail to predict. I describe three engineering design challenges that would benefit from evolutionary methods for selecting and processing information to improve decision support and knowledge synthesis:

- designing a game console,
- taking the pulse of engineering innovation, and
- geo-mapping to support preparedness and rapid response.

Though these examples differ in scale and complexity, all depend upon adaptive systems and evolvable frameworks for decision-making and knowledge synthesis. Examples from artificial life further illustrate how biodynamics inform engineering innovation. Discussion of instances where biodynamic principles apply to engineering innovation lays the foundation for an approach founded on biodynamic principles for working with cross-disciplinary teams on such problems.

CATEGORIES AND SUBJECT DESCRIPTORS

ALife, evolutionary theory, computation and engineering, complex adaptive systems, design, decision support, evolvable architectures, intelligent systems, knowledge management, knowledge synthesis

GENERAL TERMS

Design, Innovation, Knowledge Management, Performance.

KEYWORDS

Design process, evolutionary theory, collaborative problem-solving, engineering, complex adaptive systems, evolvable architectures, web 2.0

INTRODUCTION

Engineering processes that achieve civil, mechanical, and manufacturing innovation operate within "environmental contexts" that impose constraints, channeling development through iterative selection, whether or not design engineers are aware of these dynamics.

Better understanding of bio-evolutionary processes allows design of algorithms and frameworks to support complex problem-solving, adaptive evolution and innovation. Because evolutionary biologists themselves do not agree about how evolution occurs in Nature, translating evolutionary principles for engineering innovation benefits from interacting with evolutionary theorists. The following three examples illustrate how biodynamic principles are relevant for diverse engineering problems.

DESIGNING A GAME CONSOLE

A game console is a proverbial "black box." A large, cross-disciplinary engineering team designing a game console communicated through email exchange, addressing each challenge to the appropriate technical team members, with other team members cced. Cross-pollination required constant email monitoring. A vast communication record was generated.

Viewed as a bio-dynamic model, engineers' ideas are system resources. *Collaborative autonomy* describes how each individual works on the team, autonomous, with individual skills, tasks, and responsibilities, but contributing to, and benefiting from, the whole effort. In this case, ideas are species in an ecosystem, limited to a specific territory where, if they prove relevant, they survive. The many ideas in any innovation process interact to create an ecosystem. Each idea provides and/or receives resources from other ideas. Engineers bring new ideas, and technical skill to develop them, all new resources in this ecosystem.

Email communication cross-pollinates ideas, enabling robust species to evolve. The synergy of compatible ideas at any given time has a particular level of fitness relative to the problem solution. That fitness increases through developing ideas or creating new ideas, weeding out others that don't fit, while retaining those that do.

Valuable information for one team member might be noise for another. A system that could customize sorting information for each player from that player's unique perspective would be useful. A bio-dynamic decision support system would not only map the global design process in real time but also customize information-sorting from each player's perspective, so that the most valuable information for that player rises to the top of the information stack (or relevancy spectrum), while less relevant information slides down the information stack, and noise sinks to the bottom.

Imagine a decision support system where any team member can log in at any time during the problem-solving process and easily see whether the different problem-solving threads are keeping up with the critical path timeline of the process as a whole. Threads evolving are tagged at each action step (change or "mutation") and linked to the critical path of the process. Each team member is notified and can also see on the current problem-solving map when his or her expertise (resource) is needed. At key benchmarks or intervals a global view of the threads gives a big picture, building team spirit for effective product design. Management tracks threads in relation to the critical path timeline of the process as a whole. Global process-tracking positions local perspectives in the big picture. Each player's tasks lie on the critical path of game console design. Interim assessment can be performed from multiple perspectives.

How could such a decision support system invigorate the design process, increasing its capacity for innovation? In the case of this game console design project, management holds a rich repository of email lists that document the history. The design process was fast, a classic case study of collaborative design, well documented through archived email exchange, tracing the trajectory of innovation. Clear boundaries between different design tasks minimize conflicts, while allowing creative initiative. Emails across disciplinary boundaries stimulate enthusiasm and new ideas.

Although the professionals who worked on this game console design effectively used the software available at the time, new technology could

1) consider how bio-inspired, adaptive, embedded continual assessment could inform the design process;
2) redefine "fitness" or "utility," and how it is assessed in process;
3) reduce the learning curve and start-up costs to bring new resources online, learning from *The Mythical Man-Month*;
4) change the subject matter of threads over time as new problems are addressed;
5) perform global tracking, so that the system can recognize gradual changes in the project concept (species mutation) and so that any team member who bogs down can tap into the team energy and progress of the project as a whole;
6) figure out what can be automated and what cannot, and where the interface lies, since the creation of new ideas cannot be automated;
7) build an interface between human agents and automated systems;
8) develop a bio-inspired assessment tool to measure interim as well as final results (Zoebisch 2007).

THE PULSE OF ENGINEERING INNOVATION

A second, more open-ended example, lacks a clear goal or deadline. Envisage asking a community of engineers, Which cross-disciplinary research questions could apply bio-dynamic models for design process innovation in engineering with greatest success? What decision support and knowledge synthesis tools can promote collaborative progress on these problems? This could itself be a case study of bio-dynamics in design process innovation, mapping engineering research trends evolving. The Delphi Method has been used productively for consensus-seeking (Lockhorst 2004). But a next generation Delphi Method would not weed out viable ideas to achieve consensus. Instead it would converge on collaborative synergies. Threads evolving are hyperlinked to other threads as the process positions puzzle pieces in a big picture, a knowledge synthesis. Global process-tracking identifies local perspectives converging, clustering social networks of people and their associated idea kinships and dependencies.

MAPPING COLLABORATION

Often extreme applications require ingenuity that may later be applied to less demanding problems. Geo-mapping for preparedness of rapid responder teams for the next big California earthquake is one such example. The US Geological Survey (USGS) has estimated a 62% chance of a Bay Area earthquake of 6.7 within 30 years (USGS Fact Sheet, 2003). The USGS Land Use Portfolio Model (Bernknopf et. al. 2006) helps communities assess risk in a holistic way. Tools are being developed to encourage individuals, organizations, and whole communities to assess and prepare for risks. A case study of proactive participation is being developed. Information gathered from distributed agent or sensor systems is raw material for analytics and knowledge synthesis.

Exemplifying a proactive, bio-dynamic model, an experiment was developed by USGS to motivate citizen participation in scenario-building. Geo-mapping is used to support spatial decision-making and knowledge synthesis through time. Each player, from his own unique perspective asks, What information do I need to assess my risks associated with this property purchase? Perception of risks is as relevant to behavior as actual probabilities of losses. Since individuals differ in their perception of risks, and assessment of the costs of preparedness, this experiment becomes a way to survey public perception (Bernknopf et. al. 2003).

The format can refine decision support and knowledge synthesis tools: both probability and perception of probability participate in the design of innovative strategies to address risk. When a catastrophic earthquake strikes, people, resources, and strategies must rapidly align, self-organizing to respond to new needs.

DIVERSE SCALES, RELATED CHALLENGES

The first example, game console design, involves a finite team, with different skills and defined task requirements. The central focus, designing the game console, and requirement to communicate as needed, builds this community. There is a clear goal and agreed timeline — top-down management with bottom up input. Everyone knows everyone else. Collaboration is necessary to perform the task.

The second example, taking the pulse of engineering innovation, involves an open-ended social and professional network with a shared language, working in a combined competitive and collaborative framework. Though the engineering community has diverse objectives, there is potential to cluster and prioritize objectives, with advantages to those who align interests. Here there is no top-down management, so process rules must be developed that promote convergence toward shared priorities. Well-designed "game rules" enable bottom up input to self-organize.

The third example, preparedness and rapid response when California experiences a catastrophic earthquake, is the most challenging, not only because of the large number and diversity of stakeholders, but also because of the lack of clarity of the problem. Although stakeholders share community of place, resources, and interdependency, their shared needs are unclear, since the consequences of a catastrophe can never be accurately predicted. And different stakeholders have different capacities and motivation to contribute. The question for USGS is how to motivate collaboration and preparedness, how to promote the advantages of sharing information, skills, and resources. And finally, how to design "game rules" that can lead to synergetic behaviors in a high risk, unpredictable catastrophe.

The previous examples all involve decision support and knowledge synthesis. But there are many other examples in applications that range from medicine to robotics, from education to environmental sustainability, all in different ways illustrating bio-dynamic principles in innovation.

ARTIFICIAL LIFE AND ENGINEERING

Artificial life challenges bridge the divide between evolutionary biology and engineering, suggesting the relevance of artificial life as a tool to study the bio-dynamics of design process innovation. In this section I report on some of the outcomes of a think tank panel that I co-chaired at ALife X. Six proposed ideas for future challenges were:

- defining and measuring ecological complexity;
- evolving robot controllers that can outperform human-designed controllers;
- guiding evolution by shaping the evolutionary landscape;
- modeling cytoskeleton geometry and mechanics;
- creating abiotic artificial chemical cells ("chells");
- probing the *viosphere* (virtual biosphere).

Christoph Adami proposed the first three ALife challenges above. Adami notes that the ALife community has adopted different approaches to define and measure ecological complexity. Physical sequence complexity describes the complexity of species inhabiting a single niche. But, while most of life on Earth participates in complicated ecosystems, it is not clear how to define, or measure, the complexity of such assemblies. A measure of ecosystem complexity would be valuable, because ALife experiments (possibly *in vivo* experiments) could correlate ecosystem complexity with response to perturbations. Then ALife simulations could be used to form hypotheses about the impact of ecosystem complexity in the real world (Adami 1998, Lenski et al. 2003).

Second, evolving robot controllers that outperform human-designed controllers will have diverse applications. Recent success guiding robotic explorers, NASA Rovers Spirit and Opportunity, over the surface of Mars for over two years, obscures our relative inability to implant robots with autonomous navigation systems that approach the level of competence of even the simplest animals. Spirit and Opportunity are state of the art, but they are mostly driven "by hand." When observing the short tracks of autonomous driving, nobody would be fooled into mistaking this behavior as bio-dynamic: the rovers stop, record, calculate, then run blindly. Stop again, look where they ended up, recalculate, and run blindly. Attempts to encode intelligent behavior using neural networks have also failed. Current attempts use an "evo/devo" approach to develop intelligent controllers by growing and evolving neural tissues in simulated worlds. Adami proposes using ALife simulations to evolve controllers able to outperform human-designed controllers on a range of tests. ALife can improve the capacity of robots to perform intelligent applications for which robots are now being designed.

Third, in a completely different arena, Adami notes the medical hazards of bio-engineered approaches to drug design and suggests that we need to learn how to guide evolution by shaping the evolutionary landscape. Here ALife experiments could precede and avert hazardous biotechnology experiments. Work on evolutionary landscapes over the last ten years attempted to characterize landscapes, both locally and globally. We know that "we get what we select for," but generally we have no idea what we're selecting for. ALife, due to its inherent complexity as compared to mathematical simulations, can improve our understanding of evolutionary landscapes, e.g. mean distance between peaks, size of neutral networks, epistatic interaction (the interaction between genes), and so help to guide evolutionary paths towards our goals. From a clinical perspective, we also need to learn how to shape landscapes so as to prevent evolution. Evolved drug resistance is a burden for antibiotics, antivirals, and anticancer drugs. Understanding how to prevent resistant mutations could be one of the most profound contributions to public health that science could deliver.

Fourth, we should recognize not only the hazards of bio-dynamics in evolving new medical treatments, but also the potential. Donald Ingber proposes modeling cytoskeleton geometry and mechanics. Ingber's Laboratory at Harvard studies the link between cell structure and behavior. Cell shape tells the cell how to behave; modifying shape changes cell behavior. Cells spread flat are more likely to divide, while those compressed until they are round activate a death program (apoptosis); cells in between these two extremes differentiate to become tissue-specific. There's a logic to these responses. Flat cells with their cytoskeletons stretched perceive a need for more cells to fill the space; round cells perceive that there are already too many cells, so they die. Those in neither extreme condition perceive that development is going well, so they differentiate. Understanding how this switching in cell behavior occurs could lead to new approaches to cancer therapy and tissue repair, and perhaps even to the creation of artificial tissue replacements. ALife modeling might aid conceptual thinking about this challenge (Ingber 2003).

Fifth, Natalio Krasnogor proposed creating abiotic artificial chemical cells ("chells"). He also suggested a virtual "in vitro" experiment: defining virtual life within a *viosphere* so as to identify replicator signatures (metatags) that could be used to trace evolutionary activity. Such an experiment could help to define virtual life and suggest what it can teach about carbon-based life. Whether creating chemical cell life or virtual life, any attempt to synthesize lifelikeness is a lesson about life (Krasnogor 2007).

The diversity of examples described here suggests that studying how biodynamics can inform design process innovation has broad applicability in engineering. From communication and decision support in game console design to tapping a social network, from preparing for environmental catastrophe to modeling in robotics, medicine, and virtual worlds, each new challenge offers a new perspective on how bio-dynamics informs design process innovation. Our core questions, How can ideas about evolution, bio-information processing, robustness and flexibility contribute to understanding learning, innovation? And how can smart technology support innovation? These questions are also drivers for developing a think tank method.

A BIODYNAMIC THINK TANK METHOD

Designer Buckminster Fuller coined the term "synergetics" to describe the behavior of any system in which the whole is greater than the sum of its parts. Biodynamics exemplifies synergetics, showing how "synergetic evolution" informs emergent novelty in design process innovation. My method of working with cross-disciplinary teams was inspired by my early work for Buckminster Fuller, who conceived "World Game" and "anticipatory design science" (Fuller 1975).

More recently at NASA Ames Research Center I focused on collaboratory and think-tank-related program development. I envisaged a NASA think tank called BEACON (Bio-Evolutionary Advanced Concepts) that would not only bring cross-disciplinary teams together, but also be a Petri dish to culture and observe the collaborative dynamics of innovation in cross-disciplinary design teams in order to improve support for design process innovation. A series of think tank sessions, supported by a webtank (think tank on the web), can apply process models from biological evolution to collaborative problem-solving for complex NASA design challenges, such as missions into space (Gill 2001, 2003).

Whereas consensus-seeking discards ideas, this method retains divergent views as raw "genetic" material for synthesis, without requiring consensus. *Convergent synergetics* focuses the unique skills, ideas and motivation of individuals, harnessing their creativity to raise the "collaborative IQ" of cross-disciplinary problem-solving teams, whether distributed or at the same site, whether working together or unaware of each other's work (Gill 2006). Problem definition and problem- solving co-evolve, enabling innovative outcomes to emerge that could not be predicted in advance by treating the problem-solving process itself as an emergent complex adaptive system. *Convergent synergetics* achieves collaborative innovation by:

- starting from uncertainty, spiraling to a focus not predicted in advance;
- channeling the process toward unpredicted, innovative goals by using criteria for decision-making and avoiding the constraints of goal-setting;
- achieving robustness and adaptability by eliminating choke points (almost-closed doors);
- dropping pressure for consensus because richer raw material is gathered when no consensus is required;
- enabling collaborative autonomy so champions need not all agree to lead their pieces of the big picture.

Whereas workshops typically entail a fruitful exchange of ideas, networking and a report that summarizes knowledge exchanged, this bio-dynamic method enables knowledge gathering, web-supported knowledge-sharing, and think tank facilitation to achieve knowledge synthesis and unpredicted innovation. Small think tank experiments can pilot methods with potential to scale up to larger participant networks, avoiding the traditional consensus-driven constraints, while converging from general to a specific, coherent synthesis of diverse views.

This biodynamic method views the problem-solving process from three perspectives: the path (progressing through time), the frame (whole pattern resolving), and the threshold (or tipping point) — an *aha!* moment when a coherent pattern is recognized.

Three seminal thinkers inspired this approach:

C.S. Peirce thought that the terms used to describe the scientific method, induction and deduction, did not fully cover the process of the most brilliant scientists. Induction involves reasoning from particulars to the universal, or from the part to the whole. If one could see molecular assemblies becoming alive under certain conditions, one might conclude that these conditions were prerequisites for the origin of life. Deduction arrives at a conclusion from initial premises, and may find an exception, an instance when those conditions are met but molecular assemblies do not become alive. By the time Charles Darwin (1809 – 1882) published his *Origin of Species* in 1859, deduction had come to mean the process of deducing facts from laws, or effects from causes.

Because induction infers general laws from observations of particular instances, it can lead to a hypothesis. But does induction explain how all hypotheses are generated? Peirce thought not. He suspected that a third thought process required in scientific method had been overlooked. He thought this process deserved equal stature and a name.

Peirce proposed the term "abduction" to describe the leap to conceive a new hypothesis. This term has a history that dates back to Aristotle. The Greeks used *abduction* to denote a linking metaphor, or leap to a new connection, and as a term in logic to describe syllogisms in which the minor premise was only probable, rather than certain. Peirce liked that element of uncertainty. He threw down a gauntlet to future thinkers to explain "abduction" (Peirce 1934).

I propose that understanding "abduction" might shed light on how self-directed, emergent biodynamics converge toward a coherent outcome without top-down design or guidance from a goal. This is the process Buckminster Fuller termed "synergetics" through which components collaborate to create a whole that is greater than the sum of its parts and through which these wholes collaborate to create continually higher level wholes.

JEAN PIAGET

My second trigger for development of this approach was Jean Piaget's preface to Howard Gruber's study of Charles Darwin's scientific creative process. Piaget noted that Darwin needed the passage of time for ideas that were implicit in his thought to become explicit. Darwin did not conceive the idea of "evolution" full-blown and work top-down to prove his hypothesis. The concept of evolution was implicit in his early writing on variation and selection. Only later did it become explicit (Gruber 1974). I use "concept" to connote a mental pattern applied to interpret, make decisions, and act. A concept "ready to test" is a hypothesis.

In the first five editions of *The Origin of Species,* Darwin never used the term "evolution." He argued that species are modified over time by natural selection. Even "survival of the fittest," later so prominent in evolutionary theory, was not in the first edition of *The Origin of Species*. Instead Darwin spoke of "descent" and "natural selection." Twelve years later in *The Descent of Man* he referred to "the great principle of evolution," which emerged and became explicit as his work evolved (Wilson 2006). Piaget wondered how what was implicit became explicit as Darwin evolved his theory of evolution.

So Piaget threw down a second gauntlet: How does the implicit become explicit when new ideas are generated? How do ideas emerge and converge, as what has been implicit becomes explicit? How do these biodynamics reshape our world?

Curiously, design principles seen in hypotheses about the origin and evolution of life recur in explanations of how distributed multi-agent decision systems evolve toward economic collaboration and ultimately create systems able to participate in their own self-improvement (Omohundro 2007).

STUART KAUFFMAN

Biologist Stuart Kauffman explores information bits and their connections with his metaphor of Random Boolean Networks.

My third trigger was the buttons-and-thread analog that Kauffman adopted to explain how complexity reaches criticality, and then undergoes a phase transition, as ice thaws to become water or water boils to become steam. Suppose you have 10,000 buttons on a hardwood floor and a spool of red thread. You pick a random pair of buttons, tie them together with thread and return them to the floor. Early in the process, almost any button you pick will be unconnected. Gradually, as the ratio of thread to buttons increases, clusters of buttons form. Midway, you have many unconnected, largish clusters. A few more threads link these largish clusters into a super cluster. Kauffman uses the buttons and thread analog to explain how a chemical reaction network increases in complexity until the critical moment when there's enough complexity that "it could live" (Kauffman 1993, 2000).

But the buttons-and-thread analog also shows how complexity emerges by connecting simple components according to simple rules. I use it to represent an emergent method, where evolution is driven neither by a goal nor by top-down control. Both reading from word to word and tying buttons occur sequentially through time. But a big picture gradually emerges as a whole frame, becoming clearer as the network of connections grows. Linear, path-oriented problem-solving complements frame-oriented problem-solving, from blurriness to focus, as it converges, reducing error and noise.

When enough meaningful connections have been made between items of information, metaphorically represented as super-clusters of buttons tied by thread, one last connection is the link that enables its implicit structure to emerge. You "generate" a hypothesis. Your hypothesis "crystallizes" when what has been implicit becomes (*aha!*) explicit in your mind. Your last tie triggers a system phase transition.

I've just described a problem-solving model with three simple components: a path through time, a frame or big picture, which starts blurry and gradually converges into focus as pattern emerges, and the threshold or tipping point. These components are found in bio-economic models of collaboration.

BIO-ECONOMIC COLLABORATION

Bio-economic theories raise questions about entrenched Darwinian assumptions, founded in the nineteenth century marriage of evolutionary theory and the economic model of early capitalism as "survival of the fittest." To question the Darwinian paradigm requires a comparable bio-economic model for an alternative paradigm.

Some current bio-economic theorists counter the strong neo-Darwinist view that evolutionary change is solely due to competition among "replicators," which are the ultimate units of selection. If that were so, then the vast complexity of life on Earth today would be the result of sequences of mutations that happened to work and be selected to survive.

Niles Eldredge has proposed an alternate bio-economic model, assessed in cost-benefit terms. In his model individual survival impacts ecosystem survival. He emphasizes that economic success is paramount, with reproductive success as its subset: "Most adaptations are concerned with . . . . matter-energy transfer. . .[and so] are economic in nature. . . . Natural selection is the biasing effect that differential economic success has on an organism's reproductive success. . . . Organisms, with their heritable features — their economic adaptations — face an economic arena that acts as a filter, determining what genetic information is passed to the next generation" (Eldredge 1995).

Biologists, such as Leo Buss and Lynn Margulis, have examined the role of collaboration in innovation in biology. For Buss, individuality is the principle through which evolution progresses toward complexity. Collaboration describes how differentiated sub-units build new levels of individuality and new, more complex targets of selection, increasing the fitness of each new, higher level collaborating "individual" (Buss 1997).

A lower-level unit is selected by traits of the higher unit in which it collaborates, creating new units of selection: cells, organisms, kinship groups, ecosystems.

Lynn Margulis developed her Theory of Symbiogenesis and Endosymbiosis, the latter to describe the origin of the eukaryotic cell, which, she maintains, engulfs simpler cells, acquiring their attributes so that the whole behaves as more than the sum of its parts, exhibiting synergetics.

Peter Corning maintains that the neo-Darwinian focus on gene competition needs a more balanced view, shifting our focus from differential reproductive success of genes to the process of adaptation. Corning defines cooperation as any two or more parts that "operate together," whether constructively or not. An assessment of the consequences of cooperation can only be made after-the-fact. On this view parasitic relationships are cooperative. Although Corning acknowledges that cases of "intragenomic conflict" occur, he contends that the proportion of cytoplasmic gene expression that acts symbiotically is far greater. He cites a series of constructive, co-operative relationships, such as the origin of chromosomes, sexual reproduction, the division and combination of labor in eukaryotic cells, and symbiosis (Corning 2005).

Corning reviews a range of studies on "the genetics of cooperation," such as communal nesting and breeding, joint hunting and foraging, reproductive "coalitions," coordinated thermoregulation, mutual defense, mobbing behaviors.

From a different discipline, analyzing different data, physicist James Lovelock, British scientist and inventor (Fellow of the Royal Society), came to a related conclusion. As an atmospheric chemist, working for NASA in the 1960s, Lovelock analyzed infrared spectrometer readings of the atmospheres of various planets. NASA was interested in whether Lovelock's measurements suggested that Mars was a promising planet to search for extraterrestrial life. Lovelock found the Martian atmosphere to be very near chemical equilibrium, which he interpreted as the signature of a dead planet. The atmospheres of other planets in the solar system also obeyed the laws of chemistry. They were stable mixtures of gases.

But when Lovelock measured Earth's atmospheric gases with a chromatograph outfitted with his new super-sensitive "electron capture device," he found that methane existed in concentrations 10^{35} times higher than expected. Lovelock noted that the actual chemical composition of Earth's atmosphere should be highly improbable. According to the laws of chemistry, Earth's gases should have burned up long ago, making it an impossible habitat for life. These measurements were the trigger for Lovelock's grand theory of bio-economic collaboration — The Gaia Hypothesis. Contrasting the atmospheres of Mars and Venus, which are close to equilibrium, with our Earth's, which is maintained far from thermodynamic equilibrium, Lovelock determined that a planet's thermodynamic signature might be an easy way to distinguish between living and dead planets — that a planet also has a systemic metabolism, comprised of all living things and that Earth's biota might enable it to maintain its dissipative, low entropy (far from equilibrium) state (Lovelock and Hitchcock 1967).

Lovelock developed his hypothesis that the biosphere is a single living system whose parts collaborate to achieve sustainable coexistence and called it the Gaia Hypothesis (1972) — the whole Earth as a single organism. According to the Gaia Hypothesis, the way a living organism maintains homeostasis (balance) is a suitable analog for the behavior of the Earth as a whole. Such global regulation to achieve a homeostatic whole must exist as Earth constantly readjusts to maintain the subtle balance of its many interacting variables (Lovelock 1972).

The Gaia Hypothesis implies a counterpart: a universal, self-regulating decision support network to sustain the biosphere. What inspiration might we draw from this grand analogy to apply to innovation?

DISTRIBUTED DECISION NETWORKS

The buttons and thread analog can be viewed as a decision network. Buttons are bits of information relevant to a given decision. Thread defines their web of interdependencies.

While many have addressed the limitations of the neo-Darwinist paradigm, I come from a design perspective to offer a novel argument — to claim that Darwinist random variation and environmental selection through "survival of the fittest" must be complemented by a third option to explain *how* evolutionary advancement is internally driven by design principles, *why* evolution generally advances toward complexity, and the relevance of how bio-dynamics inform design process innovation.

Some key applications for distributed decision systems that manifest these principles include

- decision support systems for large civil engineering projects (Haymaker et al. 2000), which need to move beyond critical path decision-making to automate complex systems able to evolve and adapt in real time to changing time-stamped and locative data;
- automated, evolvable production systems (Frei et al. 2007), which, beyond mimicking Nature's objects, have potential to respond and adapt in context, iteratively innovating without "command and control" toward unpredicted novelty;
- evolutionary models for quick response manufacturing (Suri 2000), enabling process innovation, amenable to bottom-up triggers.

Examples of potential future applications include

- mobile telephony using multi-agent systems (Lightman 2002) to perform knowledge synthesis and analytics for decision-making about or market intelligence, economic forecasting, disease control, environmental sustainability;
- Complex, adaptive learning systems with automated updating, responsive to user input (Li et al. 2007);
- Next generation collaborative internet applications for distributed, cross-disciplinary teams (White Paper 2002).

Systems for "tapping the wisdom of crowds" have been developed, primarily for application to financial decision-making. One example from HP Labs, BRAIN (Behaviorally Robust Aggregation of Information in Networks) is an information aggregation tool that tackles prediction problems by making the prediction process anonymous, asking people to back up their predictions with real bets on where they think the numbers will land, and making it a game. BRAIN has been used for customer testing and to make resource allocations and sales predictions, and is being extended to other applications.

Huberman and his team have also developed an automatic configuration mechanism that generates the most relevant information to be presented to limited attention users of information-rich media. The system guarantees to maximize their total expected utility from the information they receive. A computationally efficient algorithm assigns an index value to each information item, determining whether or not a given item appears in the top list presented to users at a given time (Huberman 2007).

WEBTANK (think tank on the web)

The biodynamic think tank method is complemented and supported by a webtank (think tank on the web). The Webtank implements the TRACE Cognitive Model and Knowledge Processor (Gill, patent pending). Although a range of patents have issued in the fields of machine diagnostics, manufacturing, and repair, few address the application domain of collaborative group process and/or collaborative intelligence, either among humans, or involving intelligent agents. Typically the prior art focuses on diagnosis of machine malfunction, with systems designed to review received diagnostic data and determine recovery methods. And the prior art describes systems that repeatedly perform the same task, e.g. diagnosing machine malfunction based on vibrational or other data. In contrast, this system is designed to scale up, growing more complex with increasing use as it evolves its capacity for decision support and knowledge synthesis, becoming a Knowledge Bank.

Prior art has been diagnostic, correcting errors, while the Knowledge Processor is projective, providing guidance to optimize future decision-making based upon past knowledge. In contrast to prior art, the TRACE Cognitive Model and Knowledge Processor presents a guidance framework using natural language for planning, project development to support project-focused learning, brainstorming facilitation, work process monitoring, menu-based query and submission tracking through an Interactive Framework for Decision Support (IFDS).

The webtank implements a cross-platform natural language system to manage multiple data formats for collaboration and traceability, which can be embodied in software for process data management.

Applications include project development, project-focused learning, brainstorming facilitation, work process monitoring, and planning. Functionality includes capacity to manage multiple data formats, menu-based query systems, and submission tracking. Embedded Continual Assessment generates navigable, hyperlinked maps to serve the user, to analyze how the site has been used, and to map project input. Key advantages include time savings and reduction of locational bias. The risk of producing a "camel designed by a committee" is reduced by timestamping and crediting good ideas when they are shared, reducing exclusivity, peer pressure, and status dynamics (Gill 2001).

Research with think tank participants is a chance to pilot an experiment in knowledge synthesis, supported by a webtank, which allows knowledge tracing and observation of the synthesis process. Findings should be useful in scaling up to large, distributed multi-agent systems where robustness and flexibility are required.

Mechanistic dynamics can explain much about evolutionary novelty, creativity in general, and human consciousness, but an understanding of biodynamics provides tools to support innovation, which is inherently unpredictable. To be alive is to be a designer.

CONCLUSION

Cross-pollinating ideas from experts in biological and evolutionary theory and complex adaptive systems with those from experts in engineering design and innovation, exploring what these two worlds can teach and learn from each other, can

- build bridges from evolutionary biology to process innovation in engineering;
- pilot a think tank approach that supports convergence and knowledge synthesis, with potential to scale up to reach larger participant networks of decision-makers on selected questions;
- bridge disciplines, institutions, and academic and private sector researchers, translating relevant research toward engineering innovation and new ventures.

By integrating results into intelligent systems we can improve design method to impact cross-disciplinary problem-solving and process improvement, resulting in increasing innovation.

ACKNOWLEDGMENTS

The theoretical foundations for this paper are in my pair of books: Book 1. *From Mind to Microbes: Hypotheses about the Origin and Synthesis of Life* and Book 2. *From Microbes to Mind: Hypotheses about the Emergence of Intelligence* (forthcoming). I thank the many who reviewed my book manuscript for *Microbes and Mind*. From NASA Ames: Louis Allamandola, Larry Caroff, Silvano Colombano, Chris McKay. From other institutions: Mark Bedau (Reed College), Baruch Blumberg (Fox Chase Cancer Center), Graham Cairns-Smith (University of Glasgow), David Deamer (University of California, Santa Cruz), Paul Grobstein (Bryn Mawr), Stuart Kauffman (University of Calgary), Bill McDaniel (Digital Enterprise Research Institute — DERI), Victor Mossotti (USGS), Scott Turner (SUNY). I am indebted to E. Zoebisch (CEO, Riparian Software) for the suggestion to use the game console example and thoughts about how it applied, and to Scott Clearwater for discussions about distributed decision systems.

REFERENCES

1. Adami, Christoph. 1998. *Introduction to Artificial Life.* Berlin: Springer-Verlag. And Interview Keck Graduate Institute for the Life Sciences, Claremont, CA. Interview. March 2006.
2. Bernknopf, Richard L., David S. Brookshire, & Philip T. Ganerton. 2003. The Role of Geoscience Information in Reducing Catastrophic Loss Using Web-Based Economics Experiment. Professional Paper 1683. U.S. Department of the Interior. U.S. Geological Survey. Reston, VA.
3. Bernknopf, Richard L., Sharyl J.M. Rabinovici, Nathan J. Wood and Laura B. Dinitz. 2006. The influence of hazard models on GIS-based regional risk assessments and mitigation policies. International Journal of Risk Assessment & Management. Volume 6. Issue 4. 369-387.
4. Brooks, Frederick. 1975, 1995. *The Mythical Man-Month: Essays on Software Engineering*. Addison-Wesley Publishing Co.
5. Buss, Leo. 1997. *The Evolution of Individuality*. Princeton University Press.
6. Corning, Peter. *Holistic Darwinism: Synergy, Cybernetics, and the Bioeconomics of Evolution*. University of Chicago Press. 2005.
7. Darwin, Charles. 1859 [1872]. *Origin of Species*. Sixth edition. Chapter XV. "Recapitulation and conclusion." For reference to changes in the various editions, see *The Origin of Species: A Variorum Text*, edited by Morse Peckham. Philadelphia: University of Pennsylvania Press.
8. Eldredge, Niles. "Undreamt Philosophies." Foreword to Lynn Margulis and Dorion Sagan. *What is Life?* N.Y.: Simon and Schuster. 1995.
9. Frei, Regina; Ribeiro, Luis; Barata, Jose; Semere, Daniel. 2007. "Evolvable Assembly Systems: Towards User Friendly Manufacturing Assembly and Manufacturing." ISAM. IEEE International Symposium. 22-25 July. 288 - 293
10. Fuller, R. Buckminster; Applewhite, E. J. *Synergetics*. New York: Macmillan. 1975.
11. Fuller, R. Buckminster. "World Game." 1961, proposed as core curriculum for Southern Illinois University Edwardsville. Re-presented in 1964 for the 1967 International and Universal Exposition in Montreal, Quebec. Incorporated into the World Game Institute, 1972. Assets purchased by o.s. Earth, 2001.
12. Gill, Zann. August 12 – 17, 2001. Webtanks: Tools for Learning by Design. Siggraph 2001. Los Angeles.
13. Gill, Zann. 2002. Webtanks and the Management of Organizational Complexity, International Conference on Complex Systems (ICCS 2002). Nashua, NH. June 9 – 14.
14. Gill, Zann. June 27, 2006. International Conference on Complex Systems (ICCS 2006). Boston.

http://necsi.org/community/wiki/ciq on C-IQ [collaborative intelligence]

15. Gruber, Howard E. 1974. *Darwin on Man: A Psychological Study of Scientific Creativity*. N.Y.: E.P. Dutton.

16. Haymaker, J., Ackermann, E.; and Fischer, M. 2000. "Meaning Mediating Mechanism: A Prototype for Constructing and Negotiating Meaning in Collaborative Design." Sixth International Conference on Artificial Intelligence in Design, Kluwer Academic Publishers, Dordrecht, The Netherlands, 691-715.

17. Huberman, B.A. and N.S. Glance. 1993. Evolutionary Games and Computer Simulations. *Proceedings of the National Academy of Sciences. USA*. **90**.7715 – 7718.

18. Huberman, Bernardo A. and Fang Wu. 2007. The Economics of Attention: Maximizing User Value in Information-Rich Environments. HP Labs, Palo Alto, CA 94304. May 25, 2007.

19. Ingber, Donald E. 2003. Tensegrity I. Cell structure and hierarchical systems biology. *Journal of Cell Science*. **116** (7)1157 – 1173. Judah Folkman Professor of Vascular Biology, Harvard Medical School. Interview. April 2006.

20. Kauffman, Stuart. 1993. *The Origins of Order: Self-Organization and Selection in Evolution*. N.Y.: Oxford University Press.

21. Kauffman, Stuart. 2000. *Investigations*. Oxford University Press.

22. Krasnogor, Natalio, Automated Planning & Scheduling Group, University of Nottingham. Interview. March 2006.

23. Lenski, Richard E., Charles Ofria, Robert T. Pennock & Christoph Adami. 2003. "The Evolutionary Origin of Complex Adaptive Features." *Nature*. **423**. 8. May.

24. Li, L., J. Garibaldi, and N. Krasnogor. 2007. Automated self-assembly programming paradigm: The impact of network topology. *International Journal of Intelligent Systems* (IJIS). Special issue on "Nature Inspired Cooperative Strategies for Optimisation."

25. Lightman, Alex. 2002. *Brave New Unwired World: The Digital Big Bang and the Infinite Internet*. Addison Wesley.

26. Lockhorst, Ditte. 2004. "Design Principles for a CSCL (constructivist/ collaborative) Environment in Teacher Training." IVLOS Series. Published by IVLOS Institute of Education of Utrecht Universitat.

27. Lovelock, J. E. 1972. Gaia as seen through the atmosphere. Atmos. *Environ*. **6**: 579 – 580.

28. Lovelock, J. 1979. *Gaia: A New Look at Life on Earth*. Oxford University Press.

29. Lovelock, J.E. and Hitchcock, D.R. 1967. "Life detection by atmospheric analysis." Icarus. **7**. 149-159.

30. Margulis, Lynn. 1981, 1993. *Symbiosis and Cell Evolution*. First Edition. San Francisco: Freeman.

31. Mars Rover Exploration Mission and scientist comments. http://marsrovers.jpl.nasa.gov/home/index.html

32. Omohundro, Stephen M. 2007. The Nature of Self-Improving Artificial Intelligence. Keynote at the Singularity Institute for Artificial Intelligence Summit. Draft paper dated September 5, 2007.

33. Peirce, Charles Sanders. 1934. *Collected Papers of Charles Sanders Peirce, vol. 5*. Ed. Charles Hartshorne and Paul Weiss. Harvard University Press.

34. Suri, R. 2000. "Quick Response Manufacturing: A Competitive Strategy for the 21st Century," in Proceedings of the Quick Response Manufacturing 2000 Conference, Dearborn, MI: Society of Manufacturing Engineers, June.

35. U.S. Geological Survey Fact Sheet 039-03. "Is a Powerful Quake Likely to Strike in the Next 30 Years?"

36. Watson, A. and J. Lovelock. 1983. Biological homeostasis of the global environment: the parable of daisy-world. *Tellus*. **35B**: 284 – 9.

37. White paper by a national team of co-authors (including this author). "Intranets and Organizational Learning: A Research and Development Agenda." August 10, 2001. Prepared to increase research on intranets and organizational learning; published in the International Journal of Human-Computer Interaction. 14(1): 95-130. Lawrence Erlbaum & Associates

38. Wilson, E.O. Ed. 2006. *From So Simple a Beginning: The Four Great Books of Charles Darwin*. NY: W.W. Norton and Company.

39. Zoebisch, E. Interview. September 2007.