A Design Method using Darwinian Principles for Collaborative Problem-Solving Environments (CPSEs)

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Abstract: Distributed computational CPSEs (Collaborative Problem-Solving Environments) offer a petri dish where we can keep records and track creative path-finding as never before. CPSEs will enable us to test hypotheses about the dynamics of creative problem-solving that could not be tested until now.

This paper argues that Darwin's method, a daring break from the rationalistic straitjacket of his time, offers eight lessons for designers and users of CPSEs. By applying these eight lessons, CPSEs can more effectively support large scale, long-lived multi-Center and multi-project enterprises such as Mars research and mission planning. Web-based knowledge management, interactive visualization and collaborative control capabilities can evolve incrementally, transitioning into CPSEs, which will support scientists and designers to work in new ways.

My hypothesis is that CPSEs will support a new scientific revolution that could change the paradigm for "scientific method." If this hypothesis is correct, then CPSEs could drive a paradigm change in the community of practice regarding what constitutes acceptable "scientific method" and "engineering design." I suggest that CPSE design itself may also require a new synthesis, a new way of looking at scientific and engineering problems.

Keywords: distributed intelligence, participatory design, project-based learning

Introduction

A Collaborative Problem-Solving Environment (CPSE) consists of a "software workbench" with tools that can be configured and composed in many ways to construct simulations or to access, mine or visualize information.(1) In the future CPSEs should be able to:

- visualize and analyze large amounts of data;
- conduct collaborative simulation or problem-solving sessions in real-time;
- search, locate, and schedule access to resources, such as heterogeneous, geographically dispersed data repositories and scientific instrument systems;

- remotely guide laboratory experiments (e.g. on the International Space Station) in real-time or near real-time;
- support both synchronous and asynchronous collaboration;
- simulate physical and biological phenomena where experiments are impractical;
- simulate design proposals such that their characteristics can be studied in advance of full physical construction of the prototype.

CPSEs can be vehicles for "computational prototyping", cost-effective design of new products, and for new approaches to scientific research and engineering design. Challenges for CPSE design and software library structure include modularity, adaptability, scalability, and integration.(2)

Though philosophy cannot settle scientific or engineering questions, as physicist Lee Smolin noted, it can prevent us from getting hung up on a bad idea and suggest new hypotheses for us to play with.(3) In that spirit I put forward an argument for CPSE design, inspired by the way Charles Darwin "evolved" his concept of evolution. A scientist's method and content are often reflexive (method defines content which defines method); Darwin affords a particularly striking example. Because solving the creative problem of how to design a CPSE to support creative problem-solving is similarly reflexive, it could benefit from a review of Darwin's method.

Though Darwin is revered as one of history's great scientists, Thomas Kuhn's legacy was to highlight that "scientific method" is not static and immutable; it changes as scientific problems, hypotheses, knowledge and technology change.(4) Darwin's "scientific method" might have been called "unscientific" by many scientists of the twentieth century. Howard Gruber noted that in Darwin's creative process, "the search for a moment of truth is probably misguided. Perhaps the concept of a single, crucial, sudden insight is suitable for describing someone solving a well-defined problem. But we are dealing here with a different sort of thinking: a person striving to construct a new synthesis, a new way of looking at many problems, a new point of view."(5) As we move into a new millennium I maintain that scientific method is again changing, and CPSEs are at the crest of that change.

Eight lessons from Darwin for CPSE design

Darwin broke from the rationalist, analytical framework of his day to formulate a scientific theory that illustrates principles of synthesis relevant for CPSE design. In Darwin's day Creationists viewed "Design" as a divine act, so "the Argument from Design" denoted the position of Creationists who opposed Darwin's theory. Darwin focused on what he called the "laws of change"(6) which would lead to a new connotation for "design" -- design that was possible without human or Divine consciousness. In this paper I use the term "design" as Darwin might have used it, to denote a process of synthesis toward an unpredictable (i.e. not arising because of a goal), yet functional, outcome. As Terry Winograd simply stated, design generates new possibilities. (7)

Though Darwin did not conceive the idea of "evolution" full-blown and work top-down to prove his hypothesis, evolution was implicit in his early writing on variation and selection. In the first five editions of the *Origin of Species,* Darwin did not use the term "evolution"; instead he argued that species are modified over time by natural selection. Even the expression "survival of the fittest," later so important in evolutionary theory, did not appear in the first edition of the *Origin of Species*. Instead Darwin spoke of "descent" and "natural selection." Thirteen years later he referred to "the great principle of evolution", which emerged and became explicit as his work evolved. (8)

Since Darwin, evolution has evolved as a concept through the competing arguments of many thinkers with conflicting views. After more than a century, debate continues about evolutionary principles and their applications. I do not draw a broad analogy to evolutionary biology, nor take sides in this debate, nor offer any prescription for what a CPSE is or should be. Issues in evolutionary biology since Darwin, such as fitness functions, genetics, and targets of selection, lie outside the scope of this paper. My focus is on what Darwin's method offers to the formulation of a design method that could enable CPSE capabilities to evolve over time.

When Jean Piaget reviewed a case study of Darwin's scientific creativity, he made two observations. First, Darwin needed the passage of considerable time to become explicitly aware of ideas that were already implicit in his thought. And second, Piaget generalized to wonder how what is implicit becomes explicit in the creation of new ideas.(9)

1) The first lesson from Darwin is that CPSE design should start from individual projects, rather than generic disciplines.

Focus on the particular instance, the individual, the exception to the rule, represented Darwin's key break from rationalism. Conventional approaches to CPSE design develop capability to serve generic "discipline domains." Darwin reminds us that CPSE design should instead start with <u>individual</u> projects, each focused, innovative, and autonomous. Their diversity and synergies could contribute to the larger CPSE "ecosystem", a meta-level research vehicle comprised of clusters of individual projects.

In evolution an ecosystem develops gradually, through the introduction and succession of a range of species. Similarly, a CPSE ecosystem should be defined gradually by the entry of a range of participating individual players with their particular projects. A National Science Foundation CPSE Workshop recommended building CPSEs using "targets of opportunity" involving good groups of collaborators.(10)

2) Our second lesson from Darwin is a direct outgrowth of the first. By focusing on individual projects, rather than single discipline domains, CPSEs can foster research and technology breakthroughs by supporting cross-disciplinary, ecosystem-like projects.

Multidisciplinary projects cross-pollinate best where there's sufficient contextual sharing to teach, learn, exchange, and add to each other's software prototypes. The importance of cross-pollination is reinforced by the trigger for Darwin's years of inquiry: "in October 1838, that is, fifteen months after I had begun my systematic inquiry, I happened to read for amusement Malthus on *Population*, and, being well prepared to appreciate the struggle for existence which everywhere goes on . . . it at once struck me that under these circumstances favorable variations would tend to be preserved and unfavorable ones to be destroyed. The result of this would be the formation of new species."(11)

CPSE designers have identified a key challenge as integrating "multiple interacting applications" and shifting "from the current single physical-model design to the design of a whole physical system with a large number of models interacting. . . to allow the 'natural' specification of multidisciplinary applications."(12)

I propose that we view a CPSE as an ecosystem. As with biological ecosystems, in a CPSE many entities and their sub-entities are organized in various ways (both hierarchical and networked).

Community ecologists study rules of succession, through which species enter and adapt to an ecosystem, but the species remain constant. Evolutionary biologists, on the other hand, study how variation, fitness, and rules of selection change species.(13) However, all living things in nature live in ecosystems. A CPSE is analogous to "succession within an ecosystem" to the extent that ideas and tools are selected to become part of the CPSE ecosystem, but remain unchanged in that context. It is analogous to the "evolution of species" to the extent that the ideas and tools evolve and change within the context of the CPSE.

Species variation and selection occurs in the context of ecosystems. Through random variation, species pose questions to their ecosystems. So there is a necessary connection between evolution and ecosystems, which CPSEs could exploit, driving new approaches to modeling ecosystems and ecosystem-like problems. Accurate description of the interplay between species and their supporting environments could help us understand how they co-evolve over time (14) and would support my argument that CPSE development has elements of both succession and ecosystem evolution.

3) Third, each individual brings a unique subjective perspective to both pattern recognition and effective collaboration; CPSEs can be designed to track those multiple individual perspectives.

I use the term "collaboration" to refer to how unique perspectives, expertise and contributions can achieve a convergent outcome, much as an ecosystem entails the integration of varied types of participation.(15) Pilot projects with unique individual demands can bring diversity to stretch CPSE tools in different directions, as well as to strengthen collaborative knowledge-sharing and problem-solving.

Darwin's notebooks were his tools; CPSEs can revive the use of scientists' notebooks with a new twist. Electronic notebooks allow collaborators to record their individual perspectives, while CPSEs offer a unique opportunity to compare and build a synthesis from these different points of view. Through asynchronous participation they can develop their own views before sharing them in a group collaborative process.

Though we typically assume that the "scientific method" is characterized by objectivity, Darwin stressed the value of subjective impressions and interpretation. He related that he'd been accused of using the personal pronoun (I, me, my) forty-three times in the first four paragraphs of the *Origin of Species.* (16) By violating the dictum "not to write science in the first person", he demonstrated that scientific interpretation requires the scientist's subjective perspective.

4) Fourth, Darwin exemplified the use of his subjective perspective for pattern recognition.

Formerly, the primary methods of the scientist were observation, theory and experiment. Now a fourth method has been added, simulation, which has in some cases replaced experiment. Simulation, supported by supercomputing, increasingly requires pattern recognition.

By supporting increased use of human pattern recognition in visualized data or simulated phenomena, CPSEs heighten the importance of Piaget's proposed research question, the study how the implicit becomes explicit. CPSEs will provide a vehicle to study this question, using as case studies both individual researchers and collaborating groups.

In CPSEs information, graphically represented and visualized in an image, or experienced in immersive virtual reality (VR) environments, can enable viewers to use their subjective pattern recognition capabilities to find patterns and relationships in complex data that might be missed in tables of numbers.(10) We can study how research and design methods change when scientists are able to create visualizations of their scientific hypotheses using partial data or to use pattern recognition and intuition to find trends and anomalies, which they might not recognize in the data alone.

Peter Gage, an aeronautical engineer at NASA Ames working on designs for reusable launch vehicles, noted, "The important change to me is that designs are less static, more reconfigurable, both while being designed and after they are in service. If we don't finish preliminary design years before production, but keep re-evaluating decisions in the light of new information, we can retain flexibility. We might abandon the idea that design is ever finished, and allow that we can reconsider requirements throughout the life cycle and make design changes when necessary. To do this, we certainly need to archive the history of the design. We also need to exploit simulation to capture evolving operational environments. We don't need perfect simulation before construction, we need adequate simulation throughout the life cycle."(17)

Andrew Pohorille and colleagues at NASA Ames Research Center are studying the origin of life by observing visual simulations of how simple protobiological molecules organize themselves to perform basic functions required for life. Pohorille noted that the outcome of a simulation was by no means a foregone conclusion. The simulation revealed structural characteristics of this biomolecular process that the researchers could not see in the data alone. So the simulation was a discovery tool. (18) CPSEs may in the future support the extension of such research.

David Kenwright, of MRJ Technology Solutions at NASA Ames Research Center, applies evolutionary principles to the design of smart structures with the goal of self-optimization for improved performance and self-configuration for changing environmental conditions or tasks. The first application for this approach will be shape modification of a biomimetic aircraft wing. He will investigate what happens if aerospace vehicles are no longer static entities. If they are to be responsive, they must be able to dynamically change their structure as they sense and respond to their environment. Kenwright points out that there is need to develop a CPSE in which to design this type of adaptive structure. (19)

New emphasis on simulation has led to a new challenge: to integrate real with simulated systems. Sometimes it is more practical to observe real systems, other times it is more effective to simulate. One technical objective of "plug and play" should be to enable scientists to plug and play with real and/or simulated phenomena and to mix the two in augmented reality environments.(2) This capability will demand blurring the line between two hitherto separate categories of rationalist thought and method, the real and the unreal, demanding new ways to merge observation (our partial data anchors) with speculation enabled by simulation.

For example, super strong materials constructed at the molecular level will enable engineers to build structures that are currently not possible. Virtual design spaces are the only option because of the nano scales. (19) A team at the University of Texas at Austin is working on the integration of simulated and experimental data for the design of ultra-strength, fiber-reinforced materials.(20)

In the analog world between "blurry" and "focused" where pattern recognition is required, questions CPSEs will raise and help address include:

- When is it better to run lots of low fidelity simulations of alternative design prototypes rather than fewer high fidelity simulations?
- What level of granularity will optimize pattern recognition?
- How can we recognize a significant anomaly (an individual particularity or slight error that may be a key to discovery) in a simulation and zoom in?

Pattern recognition to identify significant anomalies is non-trivial; this task today requires human intuition and intelligence. Automatic feature detection and data mining tools find what they've been told to find, so they won't find anomalies that the scientist did not anticipate. In contrast, people who work for SETI (Search for Extraterrestrial Intelligence) eliminate the signals that they know (i.e., of terrestrial origin) and analyze what remains. CPSEs need similar capability to recognize visualized anomalies.(19) Though this method relies on distinguishing the two categories, familiar and unfamiliar, is it possible that that SETI will need sometime to blur this category distinction?(17)

5) Fifth, the increased use of simulation in virtual space evokes the idea of CPSEs designed as "playspaces for learning." Freed from need to predict the outcome in advance, scientists at play may discover new ways to work.

Darwin's book, *Insectivorous Plants* (1875) describes the Drosera, whose method of digestion and sensitivity (without nerves or muscles) fascinated him. He tested the glands of Drosera with saliva, drops of milk, bits of hard-boiled eggs, raw meat, albumen, cheese, dead flies, scraps of writing paper, wood, dried moss, sponge, cinders, glass, the quill of a pen, stone, gold-leaf, dried grass, cork, blotting paper, cotton wool, hair rolled into little balls, cobra snake poison, human urine, nasal mucous, decoctions of green peas and cabbage, chopped grass, and so on…...... Before assuming that Darwin was mad, we should note that his experiments were very precise. He made Drosera's tentacles move by placing on them minute particles: human hair 1/125 of an inch long weighing 1/78,740 of a gram and approximately 1/30,000,000 of a grain of phosphate of ammonia in solution. He compared the Drosera's amazing sensitivity with his own tongue's sensitivity (which could not perceive a particle 1/50 of an inch long).

Today's scientist might say, "Interesting, but is this science? What goals guided Darwin's experiments?" Darwin did not allow pre-set goals to limit the field of his experiments, though he was very precise in his method. Darwin played, and out of his play some findings were highly relevant to build his synthesis.

Darwin tested his earthworms' reaction to various sorts of light and heat and a range of sounds, including the deepest and loudest tones of a bassoon (no effect) and the vibration of a piano (which sent them whipping into their burrows). He put himself in an earthworm's shoes, so to speak: "I tried to observe what passed in my own mind when I did the work of a worm." He played their enemy, making the ground tremble so they would think a mole was pursuing them and leave their burrows (which didn't work). He made improved leaves for them (triangles of writing paper rubbed with raw fat) and superior rain (with the drops smaller and closer together than actual rain). Darwin's subjective conclusion: "Worms are timid ....When their attention is engaged, they neglect impressions to which they would otherwise have attended; and attention indicates the presence of a mind of some kind."(21)

Darwin's "play" evokes a question: how could CPSEs support explorative play as a key element in the discovery process?

6) Sixth, just as scientists using CPSEs will rely more on simulation, CPSE designers should focus on criteria for decision-making (to guide the problem-solving process) rather than goals (endpoints, objects).

Darwin held several positions that violated conventional scientific wisdom of his day. Darwin did not uphold that individual specimens were faulty imitations of a Platonic ideal or that progress gradually approximated this ideal as a "goal."

The idea that "there is no ideal", no goal, dealt a hard blow to the Cartesian notions of rationalism and essentialism. Essentialism, inspired by Plato, referred to ideal types. An outcome or individual or species approximated its ideal. Darwin's theory said the opposite: you do not start with an ideal (goal), which you approximate. Darwin started from particulars -- from individuals. The "ideal" was an average, the end of the process.

As Ernst Mayr noted, competition among individuals would be irrelevant if individuals were typologically identical; individual differences are a prerequisite for evolution.(22)

Rationalists in Darwin's time, who couldn't manage the leap from the object-focus of rationalism to the process-focus of Darwinism, interpreted Darwin's theory as the survival of the fittest (objects).

Some CPSE designers today are still mired in that object focus: a CPSE is a container (object) for toolkits (objects) comprised of tools (more objects). This object-oriented focus neglects the potential for innovative research breakthroughs when objectives cannot be stated in advance as goals -- when outcomes differ from expectations. We should recall the first recommendation of the National Science Foundation's first workshop on CPSE design for research into the architecture, **design and methodology** of CPSEs, addressing questions such as: How do we represent methods so they can be compiled into a programming language as machines and systems change? How do we modify algorithmic constituents of methods as better algorithms are discovered? (10) A cyclic approach to design is typical: "build and test cycles" in engineering, "versions" in software development.(23)

More recently, CPSE designers have recognized that existing static, network-based information repositories need to evolve into highly interoperable problem-solving service providers (2) and that repositories (objects) must be reconceived as services (processes), possibly as extensions to repositories, which will entail restructuring access.(17)

7) Seventh, CPSE designers need to keep one foot "in context" (ethnographic and other human-centered computing studies of how scientists and designers work today) but to step with the other "out of context" (recognizing that CPSEs may change our paradigm for design and scientific method in the future).

Darwin worked in a range of contexts: religious, technological, socio-economic, agricultural, scientific. In the century that preceded Darwin a technological revolution caused a shift from designing automatic machines that exemplified rigid mechanistic (clockwork) principles to designing self-regulating machines, such as temperature regulators, float regulators, and centrifugal governors, which corrected for external disturbances and readjusted to maintain the goal or desired state. Self-regulating systems were not only prominent on the invention landscape; these technological principles were manifest in the theory of Adam Smith, who argued against earlier theories of rigid, centralized control when he proposed a self-regulating economy. Though Darwin did not use this analogy to describe evolution, Wallace did: "The action of this principle is exactly like that of the centrifugal governor, which checks and corrects any irregularities almost before they become evident."(24) Darwin went further; his radical break was to suggest that irregularities were not always checked; they might evolve into new species, i.e. there is a complementarity between regulation, which conserves, and evolution, which generates new possibilities.

Similarly, in a CPSE "ecosystem", self-regulation both checks and corrects, balancing the dynamics among human players, symbiotic links among projects, computational and communication capability, tools to support information management, data analysis, visualization, simulation and collaboration. But there must also be flexibility for evolution.

The agricultural context was another backdrop for Darwin's theory. In Darwin's day, breeders used artificial selection to enhance desirable characteristics of domestic animals and achieved impressive results in a short time. Here again, Darwin broke the breeders' rules in three ways when he disagreed with the prevalent assumption that there were limits beyond which species could not be modified. First, artificial selection had at that time produced no new species (it analyzed and refined but did not synthesize or invent); Darwin made the creative leap to characterize "invention" of new species. Second, breeding required conscious goal-setting, Darwin asserted that evolution could proceed without goal-setting. And finally, human intervention through artificial selection was relatively deterministic, rather than unpredictable and inventive. Breeders produced predictable results, such as increased milk production in dairy cattle. (25)

Darwin sacrificed the sacred cow of rationalism: his theory was based, not on the rationalist notion of truth (the perfect machine or fixed species type), but rather on the heretical notion of incremental and continual change into an uncertain future. Which brings us to our eighth lesson from Darwin.

8) Finally, CPSE development demands breaking out of our current digital mindset to allow gradual, incremental progress to converge toward synthesis -- coherent, integrated design.

Darwin's theory heralded a break with classical rationalism, not only because it did not start from the collective properties of the group (type or "ideal" that an individual exemplifies), but also because it demanded that we blur the rationalist category lines of "either/or." In Darwin's time the taxonomy of living things was a focal enterprise; the word "species" was at one point a standard translation of Plato's Greek word for Form or Idea, *eidos*.(26) The great animal psychologist Konrad Lorenz noted that intellectual effort is needed to overcome western society's tendency to range the world in pairs of antitheses, mutually exclusive concepts. Lorenz maintained that this ingrained rationalist tendency is what prevented many thinkers, notably Goethe, from discovering the principles of evolution.(27) Just as Darwin blurred the either/or categories of the taxonomists, CPSEs may again blur our digital category distinctions between "either/ or."

Gradualism, which Ernst Mayr singles out as one of four key components of Darwinism, met with strong opposition because of the prevailing strength of essentialism, which influenced the view of species as fixed "types."(22) The method by which Darwin evolved his theory of evolution offers insights for a design method to "evolve" CPSE capability. If this analogy holds, CPSE capability should develop incrementally, evolving as collaboration evolves with no clear dividing line between CPSE design and its use.

Users must be involved in ongoing, evolving CPSE design. Surviving outcomes of this process, though unpredictable, will respond to the user needs that drove their evolution.

Complex enterprises, such as Mars research and mission planning, require knowledge and collaborative learning to evolve continuously across disciplines and through time. This calls for a CPSE design method that breaks out of the traditional *plan-then-implement* paradigm to adopt an evolutionary strategy for information sharing and collaborative problem-solving.

Conclusion: learning from the past, designing the future

The eight lessons from Darwin described in this paper are currently being applied to a two-year experiment in collaborative design for an exhibition and virtual museum program for the National Museum of Australia. The exhibition's key question: How will IT tools change the paradigm for scientific method and engineering design in the new millennium? Once having assessed and learned from the outcomes of this case study, applications to long term NASA enterprises are envisaged.

Would Darwin have endorsed translating principles from his theory to the human creative problem-solving process? Darwin secretly recorded his notes on human mental processes in his little known M and N notebooks (1837-9, also called the Notebooks on Man, Mind and Materialism). During this period he also worked on genetic subjects: cross-fertilization, hybridization, and sexual reproduction. Darwin delayed publication of much of his work, possibly fearing censure. And he chose not to publish his M and N notebooks at all (they remained unpublished until 1974).(5)

The Duke of Argyll described a conversation that he had with Darwin in the last year of Darwin's life (1882), "In the course of that conversation I said to Mr. Darwin, with reference to some of his own remarkable works on *The Fertilization of Orchids* and upon *The Earthworms* .... I said it was impossible to look at these without seeing that they were in effect an expression of mind. I shall never forget Mr. Darwin's answer. He looked at me very hard and said, 'Well, that often comes over me with overwhelming force; but at other times,' and he shook his head vaguely, 'it seems to go away.'" Etienne Gilson speculates that Darwin set this idea aside because in his day he could not prove it.(28)

In memorializing Darwin's theory of evolution as one of history's great ideas, we neglect that Darwin did more than break with ideas of his time; he showed the power of a <u>change in method</u>. The rationale for drawing an analogy between Darwin's method and CPSE design lies not in object-to-object correlation across the analogy, but in using the analogy to guide thinking about CPSE development as a <u>process.</u>

Outcomes of evolutionary processes can only be assessed in retrospect, not in prospect, because future outcomes cannot be predicted as goals. Similarly CPSEs, at their best, will offer rich problem-solving ecosystems where unpredicted discovery and innovation can occur. Whether CPSEs will enable us to study the process of synthesis systematically and to formulate a "design method" that is as rigorous and widely accepted as the current "scientific method" remains to be seen.

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