The Digital Earth Challenge:

from modeling Gaia to designing the future

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ABSTRACT

Digital Earth initiatives generally focus on how we will gather and integrate data — the big "how" questions. Here I focus on *why*, citing great thinkers in this last century who laid the intellectual groundwork for Digital Earth.

Now, four decades downstream, we need a new Digital Earth vision inspired by Charles and Ray Eames' film, Powers of Ten (1977), showing what we've learned since then. I make a case for how Digital Earth Collaborative Problem-Solving Environments can make it possible to grow and evolve Digital Earth to meet the grand challenge of modeling our Earth as Gaia and providing the decision support to design our way into the future.

KEYWORDS

cognition, design science, digital earth, environmental science, global ecology, hypothesis generation, limits to life, sustainability, windows of opportunity

INTRODUCTION

The combination of advanced computer simulation and visualization enables scientists to recognize patterns emerging and to link theory with scenario-building.

More than three decades ago Heinz von Foerster defined cognition as "computing descriptions of a reality." If etymology determined meaning, computing, from the Latin *com-putare*, would mean "to contemplate things" (*putare*) "together" (*com*).

Only by harnessing dynamics that engage synthesis, collaboration and emergence, can we design effectively simulate *What if?* hypotheses. Von Foerster, with uncanny accuracy, predicted the future role of computer-supported Collaborative Problem-Solving Environments (CPSEs) where simulations are not only enabled by this new computing power; their findings loop back to drive its evolution.

Now, Digital Earth is developing the foundation through which to simulate alternative future scenarios and highlight key decision points in time.

SCIENTISTS ELOQUENTLY CALL FOR ACTION

Many scientists have risen above their specialized research to sound broad calls for the cross-disciplinary collaboration that Digital Earth will make possible. On February 4, 1923 a young J.B.S. Haldane read his paper, "Science and the Future," to a society of intellectuals. He described how in 1915 he and two other Europeans walked out of a dance in India to watch a great new star explode in the Milky Way. He speculated, "Perhaps it was the last judgment of some inhabited world, perhaps a too successful experiment in induced radioactivity on the part of some of the dwellers there. And perhaps also these two hypotheses are identical, and what we were watching that evening was the detonation of a world in which too many men came out to look at the stars when they should have been dancing."

Vladimir Vernadsky, remembered for his theory of the biosphere as a whole organism, published in the year of his death, 1945, a paper on "The Biosphere and Noosphere," a term he coined, which anticipated the global brain now emerging on the internet. In his last writing he articulated his vision for the next stage of Earth's evolution into the noosphere, the sphere of reason. He warned future generations of the grave risks he foresaw for the future. He predicted that humans would take over predominance of the natural processes of the biosphere and expand into the Cosmos. He foresaw the development of new means of communication and new sources of energy. He hoped we could arrive at a time of no more war when the Earth would be able to satisfy the material, aesthetic and spiritual demands of humankind.

More recently E. O. Wilson wrote, "An Armageddon is approaching at the beginning of the third millennium. But it is not the cosmic war and fiery collapse of mankind foretold in sacred scripture. It is the wreckage of the planet by an exuberantly plentiful and ingenious humanity."

Nobel laureate Ilya Prigogine and Isabelle Stengers envisaged a sound byte: "The Age of the Machine is screeching to a halt, if ages can screech — and ours certainly seems to."

Another Nobel laureate, Christian de Duve, reflected: "There is no reason why we should view ourselves as the pinnacle of a process that still has another five billion years to go. What form the next step will take, even what extant species will be involved, are unanswerable questions. What will be recognized tomorrow as a fork organism is a mere terminal twig on the tree of life today." de Duve noted that contradictions arise if we assume that consciousness can simply be defined as a collection of neuronal events, a product of physiological brain functions. And he muses: If neuronal events in the brain determine behavior, free will does not exist. So there can be no responsibility. If consciousness is created by a collection of neuronal events, then we have no choice.

de Duve arrived finally at the metaphysical view that the universe is profoundly meaningful, in that its structure epitomizes thought and the ability to reflect upon itself. But he saw also grave dangers. He described "natural selection derailed" because of human technological advances: "What would have taken one thousand generations in the past may now happen in a single generation. Biological evolution is on a runaway course toward severe instability . . . . Our time recalls one of those major breaks in evolution signaled by massive extinctions. But there is a difference. The cause of instability is not the impact of a large asteroid or some other uncontrollable event. The perturbation is from life itself acting through a species of its own creation, an immensely successful species, filling every corner of the planet with continually growing throngs, increasingly subjugating and exploiting the world."

A lifetime of research into marine ecosystems led Sylvia Earle, marine biologist and former Chief Scientist of NOAA (U.S. National Oceanographic and Atmospheric Administration), to ask: "Could certain microbes, now occupying highly specialized, restricted niches, find the conditions we are creating more favorable and enjoy population explosions that trigger other events inhospitable to us? Changes in the sea in the past few decades should command our rapt attention — the sort of interest one might take in, say, the life-support system of a spacecraft housing all of the past, present, and future of humankind."

Many have dismissed Sir Frederick Hoyle's ideas about the origin of the universe and the origin of life. But his translation of the not-enough-time problem from the origin of life to its future deserves a hearing: "I am haunted by the conviction that the nihilistic philosophy, which so-called educated opinion chose to adopt following the publication of *The Origin of Species* committed mankind to a course of automatic self-destruction. A Doomsday machine was then set ticking. Whether this situation is still retrievable, whether the machine can be stopped in some way, is unclear."

And Bill Joy mused: "People who know about the dangers still seem strangely silent. When pressed, they trot out the 'this is nothing new' riposte — as if awareness of what could happen is response enough. . . . They complain, 'Your worries and your arguments are already old hat.'"

Late in life the great animal behaviorist Konrad Lorenz offered an optimistic vision: there were in his view definite signs that a self-recognition of all cultural humanity, a collective self-knowledge derived from natural science, was beginning to spring up. Lorenz believed that if this movement grows, human intellectual aspirations and energies will be raised to a higher level of integration, a "creative flash" of reflection and meditation. And he noted that a reflecting, self-investigating culture has never yet come into being on this planet, just as objective science did not exist before the time of Galileo.

IMPLEMENTING KONRAD LORENZ' VISION

How can Digital Earth bring about Lorenz's vision of a higher level of integration — this "creative flash" of a reflecting, self-investigating culture?

If today we all have our noses to the grindstone, doing the next scientific experiment or inventing the next little tool, we may miss the chance to see the future realities that our experiments could support and that our tools could be designed to sculpt.

In throwing a catapult, each individual wind cannot be assessed in isolation. It is the synergy of all the winds taken together that produce an outcome, which can be assessed. For human civilization we now need the synergy of individual actions to be integrated toward constructive impact on the ecosystems of the future. Digital Earth is the great integrator that can bring about that synergy.

Key principles exemplified in Nature apply to designing collaborative problem-solving environments with the Digital Earth integrative framework, offering decision support for complex, cross-disciplinary sustainability challenges.

Collaborative autonomy is the dynamic through which autonomous units, whether molecules collaborating to invent life, or organelles collaborating to make a functioning cell, or arguments collaborating to construct a hypothesis, or humans collaborating to solve a problem, bring their uniqueness and autonomy to the collaborative process. Applying this principle of Nature to human problem-solving avoids the lowest-common-denominator consensus of committees, where individual uniqueness is lost by weeding out diversity to achieve consensus. Collaborative autonomy preserves "genetic diversity," rich raw material that makes for effective evolution, both in Nature and in human problem-solving. Digital Earth can coordinate a diversity of collaborators while maintaining their collaborative autonomy — their capacity to champion their pieces of the big picture.

Avoiding choke points is a prerequisite, both for the origin and evolution of life, and for human problem-solving. A choke point is a required, but unlikely, contingency, a link that might break the chain of events required to originate life. Origin of life theorists have stronger hypotheses when they can identify alternative pathways, scenarios, and events that would have been highly probable on early Earth. Similarly Digital Mapmakers need to identify alternative paths toward sustainable futures. We cannot lock ourselves into only one path.

Harnessing uncertainty starts from lack of definition, where many alternatives are equally possible. Gradually it gives up possibility as specification defines novelty, converging in toward its focus, as a design process converges toward the solution that responds best to the constraints of its context. Digital Earth itself evolves toward greater and greater definition as data is gathered, integrated, and iteratively adjusted in response to other data to build a consistent whole. Through continual adjustment, much as building a tensegrity structure requires continual adjustment of its parts to the whole, can Digital Earth begin to model the Gaia Hypothesis.

Overlapping tolerance windows define what variations are possible and guide evolutionary emergence. Greater tolerance opens wider windows of possibility for evolution. Tolerance windows also enable us to understand extinction and ecosystem collapse, offering a way to integrate data into the Digital Earth framework.

Forming criteria to accept/ reject interim results is an alternative to Karl Popper's model of the growth of scientific knowledge, which tested only the final result, lacking capacity to recognize partial patterns emerging and bring them into focus.

These principles underpin the integration of Digital Earth's diverse data and technologies.

THE GAIA HYPOTHESIS

Physicist James Lovelock, British scientist and inventor (Fellow of the Royal Society) conceived the Gaia Hypothesis of collaboration in the biosphere, which Digital Earth technology enables us to study.

The diversity of ways bacteria found to make a living led Sergei Vinogradsky to wonder if these individual solutions were small puzzle pieces in some larger system. In a lecture to members of the Imperial Institute of Experimental Medicine on December 8, 1896, Vinogradsky voiced an idea reflected more recently by James Lovelock and others: One cannot but view inanimate nature as an integral whole, as one huge organism, borrowing its elements from reservoirs of the inorganic world, controlling all processes of its progressive and regressive metamorphosis, and finally, giving back to dead nature all that has been borrowed.

Starting from different data, Lovelock came to share Vinogradsky's view. 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 might suggest 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.

Lovelock first propounded the theory that the biosphere is a single living system whose parts cooperate to achieve sustainable coexistence. He called it the Gaia Hypothesis — the whole Earth seen as an organism.

The Gaia Hypothesis exemplifies dynamics described by biologist Leo Buss. If evolution advances by resolving conflicts among lower level units, such as cells, to make organisms on a higher level, then individuality is the result of effective collaboration. The global collaboration proposed by the Gaia Hypothesis might have come about through an upward emergence of collaborative systems, from lower levels to higher.

Lovelock's development of The Gaia Hypothesis illustrates the trajectory from interpreting data to developing a hypothesis, augmenting that hypothesis with further evidence, simulations, and finally its debate within the scientific community.

Lovelock conceived the Gaia Hypothesis through interpretating an inconsistency: the atmospheres of Mars and Venus are close to equilibrium, while our Earth maintains an atmosphere far from thermodynamic equilibrium. These observations, made while Lovelock served as a consultant to NASA on the design of a mission to Mars, led to his hypothesis 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.

Lovelock then wondered how to accommodate one seeming contradiction of Earth's far-from-equilibrium signature. He hypothesized that Earth's biota might enable it to maintain its dissipative, low entropy (far from equilibrium) state.

The story behind the Gaia Hypothesis illustrates how hypotheses are developed. An individual has an idea: scientists traditionally assumed that life is nested inside its biosphere. But Lovelock thought we should ask a more basic question before we assume that our biosphere is simply the context for life: What if we see our biosphere, not just as life's context, but as itself alive?

Lovelock's Hypothesis (1972) was that the way a living organism maintains homeostasis (balance) was a suitable analog for the behavior of the Earth as a whole, that such global regulation to achieve a homeostatic whole must exist, and that the Earth must be constantly readjusting to maintain this subtle balance of its many interacting variables.

Lovelock's Gaia Hypothesis that the biosphere can be viewed as a living organism first met with resistance and disbelief, and later aroused debate. Although it appeared plausible, based upon observing Earth's unique atmospheric behavior, since it was based solely on observation, Lovelock could not prove it.

Lovelock joined biologist Lynn Margulis to develop ways to confirm the Gaia Hypothesis. The Gaia Hypothesis was refined to focus on how life on Earth might regulate Earth's atmosphere to make it suitable for life. Another loop.

GAIA AND THE COLLABORATIVE PARADIGM

The Gaia Hypothesis raises new questions about evolution as "competition for survival of the fittest." If the Gaia Hypothesis is correct, and Earth with its biota acts as a homeostatic, geophysical, systemic organism, able to regulate its global properties, such as temperature, we have living proof that competition for survival of the fittest is a subordinate mechanism to the grand collaboration that makes Earth a livable planet — the collaborative complex system that Digital Earth aims to model.

The Gaia Hypothesis supports the postulate that collaboration must subsume competition. Otherwise, how could local selection among locally competing species ultimately produce the global collaboration among species and their ecosystems that would regulate Earth as a whole system? How could Darwinian competition alone support global collaboration?

Lovelock's macro perspective led him to conceive the Gaia Hypothesis, which has now attracted the interest of a range of artificial life. Their simulations suggest that collaboration may be a key driver of evolutionary change. Lovelock took sides in the competition versus collaboration debate, seeing collaboration as a long term strategy, rather than a sequence of ad hoc adaptations. While the Gaia Hypothesis has had its share of detractors, many distinguished scientists, such as Christian de Duve, Freeman Dyson, Lynn Margulis, and Lewis Thomas, recognize Lovelock's hypothesis as an important contribution.

The Gaia Hypothesis contradicts our traditional assumption that competition for survival of the fittest was the overarching principle, with occasional minor collaborations as subsets within that larger competitive framework. If collaboration is Nature's primary operating principle, with competition as its subset, then our biosphere is itself a Gordian knot of interacting, collaborative feedback loops, through which life develops and maintains an environment suitable for its continued existence.

How does Earth evolve and maintain its exquisite balance? Homeostasis (this continual balance) is not static; it is a continual balancing act, requiring constant readjustment. To understand this continual rebalancing, I'll introduce the tensegrity metaphor.

DAISYWORLD AND OTHER SIMULATIONS

The Gaia Hypothesis is hard to study because of the complexity of the interdependencies that it describes. Digital Earth may eventually make this study possible. Gaian researchers search for micro scale examples of self-balancing interactions. The macro-scale hypothesis seems to be borne out on a micro-scale by local regulatory effects of cooperative, distributed ecosystem strategies to control local climate, marine salinity, and nitrogen-phosphorus ratios. So algae play a role in homeostatic loops where they control microclimate in regions where they live.

A decade after proposing his Gaia Hypothesis, his analog of the Earth as a living organism, to gain acceptance for that hypothesis, Lovelock, working with AJ Watson, proposed a second analog, Daisyworld (1983), to explain the mechanism through which atmospheric regulation might occur. The Daisyworld analog was a simplified model containing only black and white daisies, regulating only one variable, temperature.

A computer-based simulation illustrated how distributed planetary temperature regulation might emerge. In a simulated Daisyworld black (non-reflective) and white (reflective) daisies grow, together regulating local temperature. At the optimum 22.5° C., black and white daisies grow in equal numbers. During cold spells, black daisies increase, driving temperatures up. In hotter times, white daisies dominate, driving it down.

Daisyworld, though a radically simplified model for homeostasis, is non-trivial to calculate, and it has attracted the imagination of many researchers, particularly in artificial life. Keith Downing's artificial life model, Guild, simulated evolutionary emergence of heterogeneous groups of organisms (guilds) that consume and recycle particular products, thereby collaborating to regulate their environments. These cycles combine biotic and abiotic feedback, emphasizing the seamlessness of collaboration across living and non-living systems. Daisyworld has also been generalized to describe how any behavior, guided by both positive and negative feedback, leads to homeostasis.

Olsson et al., inspired by the Gaia Hypothesis, speculated, Suppose we view an effective ecosystem *as* a single organism. How might informational constraints drive the evolution of sensor layouts in that ecosystem if fitness were weighted for redundancy versus novelty? Theirs was a first step toward a Digital Earth model of the Gaia Hypothesis. They studied how biological sensors could evolve that would enable organisms to survive and reproduce, and how selective pressure for either redundancy or novelty would affect the evolution of sensor layouts.

Some qualifiers: symbiosis or mutualism (one-to-one), collaborative groups or ecosystems (some-to-some) and Gaian models (everything networked to everything else) lie on a spectrum of collaborative interactions. What is learned from a one-to-one study of symbiotic behavior cannot be automatically translated to a Gaian model, or vice versa. Qualitatively different outcomes may arise from behaviors in different models. So modeling has inherent risks of misinterpretation.

TENSEGRITY AND DIGITAL EARTH

Tensegrity appears to hold clues for how life might have begun and maintained itself in a changing environment and for how Digital Earth can study the Gaia Hypothesis — the iterative adjustment of the biosphere with its complex overlay of tolerance windows.

Kenneth Snelson, an engineer turned sculptor, was inspired to discover tensegrity structures by Buckminster Fuller in 1948 at Black Mountain College, then a famous summer program to spawn creative thinking. Snelson worked through the fall in Oregon and returned the following year to show his discovery to Buckminster Fuller.

Fuller, known for his geodesic domes, realized that Snelson had discovered an important principle, which Fuller called "tensegrity," an abbreviation for "tensional integrity," a system that maintains its integrity through a continuous web of tension connecting discontinuous compression members. So a tensegrity structure achieves structural integrity through a separation of perfectly balanced, opposed forces. The significance of tensegrity structures is only beginning to be recognized.

A balloon illustrates the tensegrity principle: the air pushing out (compression) is perfectly balanced by the membrane (tension) pulling the air in. In tensegrity structures the tension wires, which play the role of the balloon membrane, pulling the structure together, are connected. In contrast, the compression struts, which play the role of the air, pushing the structure apart, are disconnected. In tensegrity structures these opposing forces are balanced, enabling the structure to morph in response to external load. Tensegrity structures contrast with structures dependent on gravity, which are characterized by compressional continuity.

Like life, every part of a tensegrity structure is dependent upon, and collaborating with, every other. Tensegrity structures illustrate "collaboration" as a purely mechanistic dynamic in a structural system. They lack structural integrity until all parts are effectively *collaborating*. Unlike compressional continuity, which characterizes structures dependent on gravity, because in tensegrity structures no compression member touches any other, compression members must be connected via a tension web. So these structures are defined by their balance of opposed forces.

Tensegrity structures illustrate a mechanistic "collaboration" through iterative adjustment, much the way a Digital Earth model of Gaia would need constant adjustment to achieve a balanced participation of collaborating components, maintaining global *homeostasis* through time. Homeostasis is the ability of a system to self-regulate and maintain a particular state, keeping its internal environment stable while the outside world changes. The mechanical stability of tensegrity structures comes from distributing and balancing stress over the entire structure. Their lightweight individual components become strong through "collaboration."

Continuous global tension enables the structure to respond in an integrated way as a whole to any local perturbation. An anomaly introduced anywhere in the structure will ripple out to the whole, progressively dampening as it spreads outwards. A variation introduced anywhere will elicit a "collaboration" of all components to produce a response from the whole.

Iterative adjustment continues as the structure responds over time to its environment. In tensegrity structures, although this response is purely mechanical, it illustrates a mechanistic precursor of autonomy, an integrated response generated internally by the whole structure. In living organisms closure, completion of the adjustment cycle, is stasis, death of the organism, because it has lost its capacity for further adjustment. So too for our Faian biosphere, so no static Digital Earth model could represent it; models must evolve and adjust through time.

So for life to live, its collaborating components must be continually adjusted.

After studying tensegrity structures, I eventually went myself to work for Buckminster Fuller in order to continue research on these structures. But my motivation was different from Snelson's. I didn't aspire to build magnificent sculptures. I was fascinated by the tensegrity principle and its separation of perfectly balanced, opposed forces. I intuited that it might hold clues to the mystery of life's constant demands for "balancing" of thermodynamic forces, osmotic pressure, and chemistry.

In a tensegrity structure every element is co-dependent upon, tuned, and balanced with every other. Tensegrity structures have no stability until completed. They collapse even as you try to build them. Only when the very last wire is in place and the entire structure perfectly balanced, do they exhibit structural integrity.

Tensegrity is a metaphor for how the components of life must be perfectly tuned and collaboratively balanced with each other for life to live. This metaphor suggests the great intricacy and fragility and uniqueness of Earth's present exquisite balance, highlighting why Digital Earth must model and study that balance.

THE RARE EARTH HYPOTHESIS

The Rare Earth Hypothesis of Peter Ward and Donald Brownlee contends that microbial life is common, but complex animal life is very rare. They ask a provocative question with moral implications, "What if the Earth, with its cargo of advanced animals, is virtually unique in this quadrant of the galaxy — the most diverse planet, say, in the nearest 10,000 light years?

"*What if* it is utterly unique: the only planet with animals in this galaxy, or even in the visible universe, a bastion of animals amid a sea of microbe-infested worlds? If that is the case, how much greater the loss the Universe sustains for each species of animal or plant driven to extinction through the careless stewardship of Homo sapiens?"

Then our Earth itself is a tensegrity structure — an Ark perfectly balanced through billions of years of subtle adjustment.

The Rare Earth Hypothesis emphasizes the great need to collaborate across the divides of technology and activism, across the lines of scientific disciplines. Digital Earth represents a radical break from academia as usual — academia rolling up its sleeves to work outside the ivory tower on the biggest challenge Planet Earth has ever faced — sustaining life on Earth.

CONTEMPLATING REPLICATIVE HAZARDS . . .

If evolution produces new materials and embodiments that can take over the role of humans, these alternatives will evolve, not as a sudden shocking event, but as a transition so subtle and gradual that it can happen without the awareness of most of the human race. There are whistle-blowers to be sure, just as there are whistle-blowers about environmental degradation. But who is listening? And the new, non-carbon-based creatures may not need the natural environment. They may be adaptively superior, both in space and on the transformed Earth that humans are now creating for them. Like the famous frog in the puddle, where the temperature was raised so gradually that the frog never noticed and boiled to death, the change may be so gradual that we just won't notice.

Manfred Eigen speculated, "Today we can intervene in, and repair, genetic processes; this capability asks for knowledge that we don't yet have. Future evolution will be not only on the genetic level; the human mind enables a faster roundabout of development. What happens in the future will involve humankind. Now, as before, the motto of evolution is still survival."

Digital Earth mapmakers could create dynamic maps showing the trajectory of population increases in different regions of the world and contrasting those increases with the trajectory toward extinction of vital species in those regions.

We are forewarned by population biologists of human replication beyond what the planet can sustain and by computer scientists of replication in a different form — the self-replicating loop in computer code that enables a universal constructor to copy itself.

Replication, and evolution arising from the ability to replicate, underpins all the wonders life has evolved. Successful replication of some species has led to the extinction of others. But now, as computer scientists speculate about the future, fears arise that this same foundation of all life could also bring us full circle to our own extinction. In "computer networking. . . the sending and receiving of messages creates the opportunity for out-of-control replication. . .

"The 21st century technologies — genetics, nanotechnology, and robotics (GNR) — are so powerful that they can spawn whole new classes of mutations and abuses. Most dangerously, for the first time, these mutations and abuses are widely within the range of individuals or small groups. They will not require large facilities or rare raw materials. Knowledge alone will enable use of them."

"Thus we have the possibility, not just of weapons of mass destruction but of knowledge-enabled mass destruction (KMD), this destructiveness hugely amplified by the power of self replication." This prospect led Chief Scientist of Sun Microsystems Bill Joy to a sobering reflection: "Failing to understand the consequences of our inventions while in the rapture of discovery and innovation seems to be a common fault of scientists and technologists. . . . As this enormous computing power is combined with the manipulative advances of the physical sciences and the new, deep understanding in genetics, enormous transformative power is being unleashed. . . . But now, with the prospect of human-level computing power in about 30 years, a new idea suggests itself: that I may be working to create tools which will enable the construction of the technology that may replace our species. How do I feel about this?"

How will the Digital Earth research community protect its data and assure its productive use?

CONCLUSION

How can we begin to speculate about our many possible futures from a new perspective that is more than an argument, more than the marshaling of data, a perspective from which we assume responsibility for the design of our futures? The Gordian knot is tied with many threads — the paths we choose as we speculate, act, interweave our ideas and collaboratively design our way into the future. Our journey into the unknown will be driven by our innate curiosity, our unique ability as conceptual thinkers to speculate, and by thought itself evolving.

How does speculation drive scientific discovery? How can we design contexts for collaboration to turn speculation into hypotheses? Data fits into patterns, communicating messages that we must interpret.

Renowned paleontologist Niles Eldredge, who co-developed the Theory of Punctuated Equilibrium with Stephen Jay Gould, in a poetic piece, "Undreamt Philosophies," raised a series of questions that one might not expect from a student of the fossil record: Why has evolution crafted sentient species? Why did our consciousness, our realization of our very existence, evolve?

Through scenario-building to explore our origins and futures we arrive at new syntheses that could as radically change our concept of ourselves in the universe as did the explanation of Copernicus that our Earth is not the center of the solar system, or Darwin-Wallace's description of evolution.

If we accept uncertainty, we will worry less about defining the future as a goal. Instead we should examine carefully the criteria that guide our transitions from the present into the future. What are our values? How do these values affect our choices? What "moral imperatives" have we taken for granted as defining our possible futures? What "singular anomalies" that could trigger great change have we ignored?

E.O. Wilson reminds us that Darwin's discovery of evolution was a humbling revelation: "Humanity is not the center of creation and not its purpose either. But in freeing our minds from our imagined demigod bondage, even at the price of humility, Darwin turned our attention to the astounding power of the natural creative process. . . ." — the evolution of our Earth through time that Digital Earth will model.

And Karl Jaspers wrote, "We cannot transcend this world by our knowledge of something, but solely by the course we take within it, by the experience of the Ideas in systematic knowledge, by the play of all our cognitive faculties in the intuition of the beautiful, and truly and decisively, through our freedom in ethical action."

So we acknowledge the paradox of prediction. The future does not yet exist for us to observe or predict. But with the decision support of Digital Earth, it awaits our design . . . .

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