General Summary

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Jorge Luis Borges wrote of an imagined regime that had so mastered cartography that it could create giant, detailed maps, and its crowning achievement was a map of the empire that was the same scale as the empire itself, replicated locations coinciding one-to-one.

> Less attentive to the study of cartography, succeeding generations came to judge a map of such magnitude cumbersome, and, not without irreverence, they abandoned it to the rigors of sun and rain.
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> "Of Exactitude in Science" from J.L. Borges, *A Universal History of Infamy* (1935)

The challenge presented to the 2008 attendees of the National Academies Keck *Futures Initiative* on Complex Systems was to understand systems as complex as the world itself, with models that are necessarily nuanced to contain enough detail to be useful, while not being so complex as to render those models as impossible to build or understand, and thus relegate them to the deserts of our minds.

Keck board member Richard N. Foster offered a relevant piece of advice to advance thinking on the project; that, like chess masters pondering the small problems of skirmishes and macro problems of the whole game, scientists must learn to effectively "zoom in and zoom out" with their minds.

Network research expert Albert-László Barabási gave the conference a rapid-fire overview of his theories of scale-free networks, that is, naturally emerging but ordered systems whose distributions follow an exponential increase. He described the Internet as "architecture of complexity" that is "driven by our own activities but beyond the comprehension of those who create it."

"How is it possible that they have the same underlying structure," Barabási asked before the panel of hundreds of experts. "And so what? Does it have any consequence?"

Being able to fit a line to the data does not mean we can understand and control the behavior of neurons in a seizing brain or can better build and harden a computer network from attack. But such a grand set of notions helped bring the problems into finer focus for the groups about to meet and tackle their various topics related to complexity. In the words of presenter Dr. Harvey V. Fineberg, president of the Institute of Medicine, the groups decided "which problems are just ripe enough to pick from the tree."

Each task group contained about a dozen experts from many different fields: engineers, microbiologists, computer scientists, economists, mathematicians, paleontologists and neurologists, among others. A graduate science writing student, assigned to every task group, was given the equally stimulating task of somehow capturing the essence of the process, the product and the possibilities that emerged in the discussions.

Task Group 1 tackled the question of how to design the acquisition and organization of the data required to completely model human biology.

Their assignment was to simulate the complex functions of the human body, a job they acknowledged "is larger and more complex than the human body itself."

The group began by drafting a five year plan for collecting and checking biological data, the first step in building the living, breathing simulation of the human body which would not only vastly enhance research but which is an enormous research challenges in and of itself.

Task Group 2 explored what it takes to achieve a sustainable future. The group noted the urgency of the problem, asking, "if not now, when?" and planning a variety of modeling techniques for charting environmental and social degradation, as well as several complex-systems modes for recovery. They concluded that a neural network modeling technique, like that used in brain research, is necessary to tackle nonlinear, holistic issues on planet Earth.

Task Group 3 dealt with the issue of enhancing robustness via interconnectivity. "In many identifiable systems, such as power grid structures, disaster relief networks, airline traffic systems, the Internet and yeast genetic interactions," the group concluded, "the ideal situation that allows robustness to be enhanced is one where both performance optimization and perturbation can be specified." They suggested that vertical connection between hierarchical networks is one solution, as is a "toggle" ability to switch between distributed and centralized organization.

Task Group 4 asked if engineering systems and control approaches can generate new strategies for altering imbalanced macrophage profiles in human disease.

Given the assignment of determining whether cellular and genetic engineering can restrict the growth of cancer, they asked: "Should the focus be on changing M2 macrophages into M1s, or on preventing the development of M2 macrophages in the first place?"

They asked, "Would simply eliminating all M2 macrophages create a tumor fighting phenotype, or should the control system also generate more anti-tumor M1s?"

In the end, Group 4 found that though exerting control on disease spread might be possible, it might be so complex as to be prohibitive. "In the end, it's quite possible that systems to control cell fate might turn out to be just as complex as the organisms they're meant to control."

Task Group 5 pondered social networks' capacity to aid our understanding of complexity. The Internet as a tool for taking snapshots of trends in real life and cyberspace piqued the group's interest. They concluded that mapping a "moving picture" of progressions of diseases and ideologies across the Web would be a valuable first step in using social networks as a already-built sensor system for society.

Task Group 6 handled the brain and the future of understanding the complex, linked interactions among the many types of neurons in the brain. Will that knowledge lead to knowing how the brain contributes to normal function and susceptibility to neuropsychiatric disease?

"An elephant's brain has about four times as many neurons as a human's, but we would assume it is less complex," the group noted.

"It is the organization—not sheer number—of the brain's connections that result in intelligence; complexity captures this organization." And knowing that, how can we engineer computer models, medical interventions or information systems that derive more nuanced function with fewer moving parts?

They settled on an impulse-control model as a metric of complexity, writing "We would compare these different measurements between organisms with different abilities to control their impulses—different strains of mice, different species, humans with certain diseases, and humans with different skills, such as artists and scientists. This will reveal which aspects of the brain's organization are related to impulse control."

Task Group 7 posed questions about enhancing the robustness of engineered systems, and how can the methods of engineering analysis be extended to address issues of complexity and management in other fields. The discussion soon turned to the possibilities of self-regenerating automobiles, space shuttles, a house that could repaint itself, roads that fix their own potholes, and so on. The group's consensus was that by blending the lessons from biology with the lessons from engineering, making machines that heal in a lifelike way could absolutely bolster robustness.

Task Group 8 focused on ecological robustness and in specific, the question of whether the biosphere is sustainable.

Ultimately, the group concluded that preventing the destruction of an ecosystem is far more feasible than rebuilding it. Robustness means not having to clean up the mess in the first place, the group decided. “The models and experiments will reveal projections of ecosystem futures, and what we can do to steer the biosphere towards a path that will sustain humans for generations to come,” the group agreed.

Task Group 9 shouldered issues of controlling flow and transport in complex systems. They recognized the importance of not being seduced by broad generalizations about all networks based upon appealing patterns in a single one.

“It is important to remember that the unique subtleties of individual networks and the dynamics along that network …affects the means of control along that network,” the group agreed.

The other half of Group 9 explored damage control in complex systems. In the wake of the recent economic collapse, the group sought to use Google-search red flags, as has been done with flu outbreaks, to warn of coming economic collapse. Group members postulated that two forces govern information and financial flow—gain and fear—and that such a warning system could alert those in control of interest rates and other relevant financial data to rapidly react when the system switched from pursuit of wealth mode to avoidance of loss mode.

Taken as a whole, the challenges are both mechanical and epistemological, both chemical and philosophical, and the questions are the ones that will define us as a species within our ecosystem. From fighting disease to reversing environmental damage, the quest to effectively model our bodies, our social groups and our effects on the planet is a profoundly important one. As explorers, we must seek to replace the indistinct regions on our maps with meaningful topographies, and in so doing, better know ourselves.