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Knowledge Magazine

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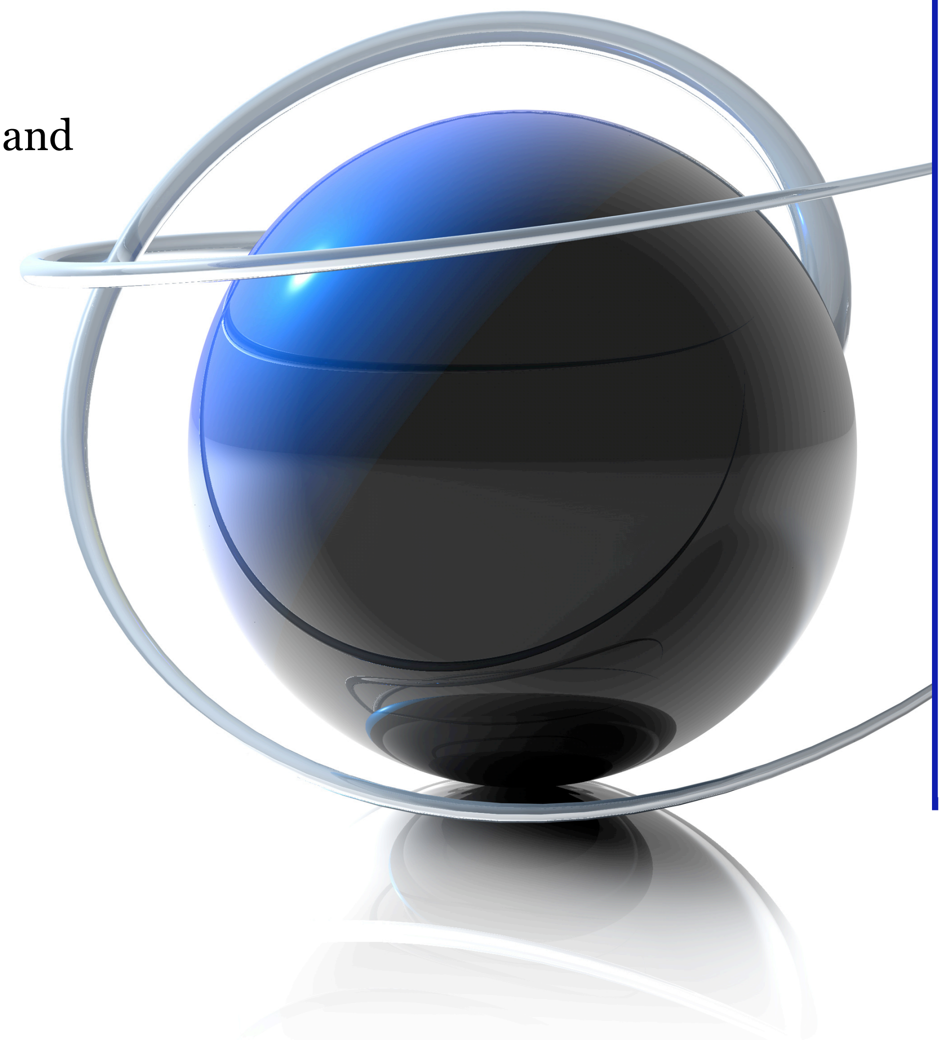

INAUGURAL ISSUE

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The Quarterly Publication of The New England Complex Systems Institute

Knowledge Magazine is published by The New England Complex Systems Institute (NECSI) to inform those interested in cutting-edge science and its applications. Four times a year, Knowledge Magazine brings you to the frontiers of scientific insight. Find out more at: www.knowledgetoday.org.

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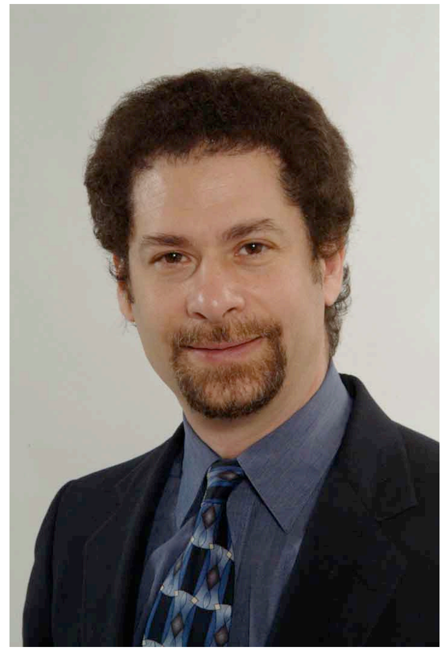
Message from the President



Prof. Yaneer Bar-Yam, President of NECSI

Welcome to the inaugural issue of *Knowledge Magazine*, the quarterly publication of The New England Complex Systems Institute. Four times a year this magazine will provide valuable insight to those interested both in research occurring at NECSI, as well as complex systems' relevance to many present day challenges.

In this issue NECSI researcher, Dr. Justin Werfel, considers the dangers of human extinction and how we might avoid it. His feature "Modeling, Communication, and Global Catastrophe" offers a sobering look at the crucial role science must play in the near future.

This issue also features exciting new insights into the problems of the healthcare and transportation systems. In both cases we apply the latest breakthroughs in complex systems science to offer new solutions to old problems.

As we prepare for a new year, a new administration, and new challenges, cutting-edge scientific research is more important than ever. It is an exciting time for the pursuit of knowledge. Thank you for reading, and I hope you enjoy the issue.

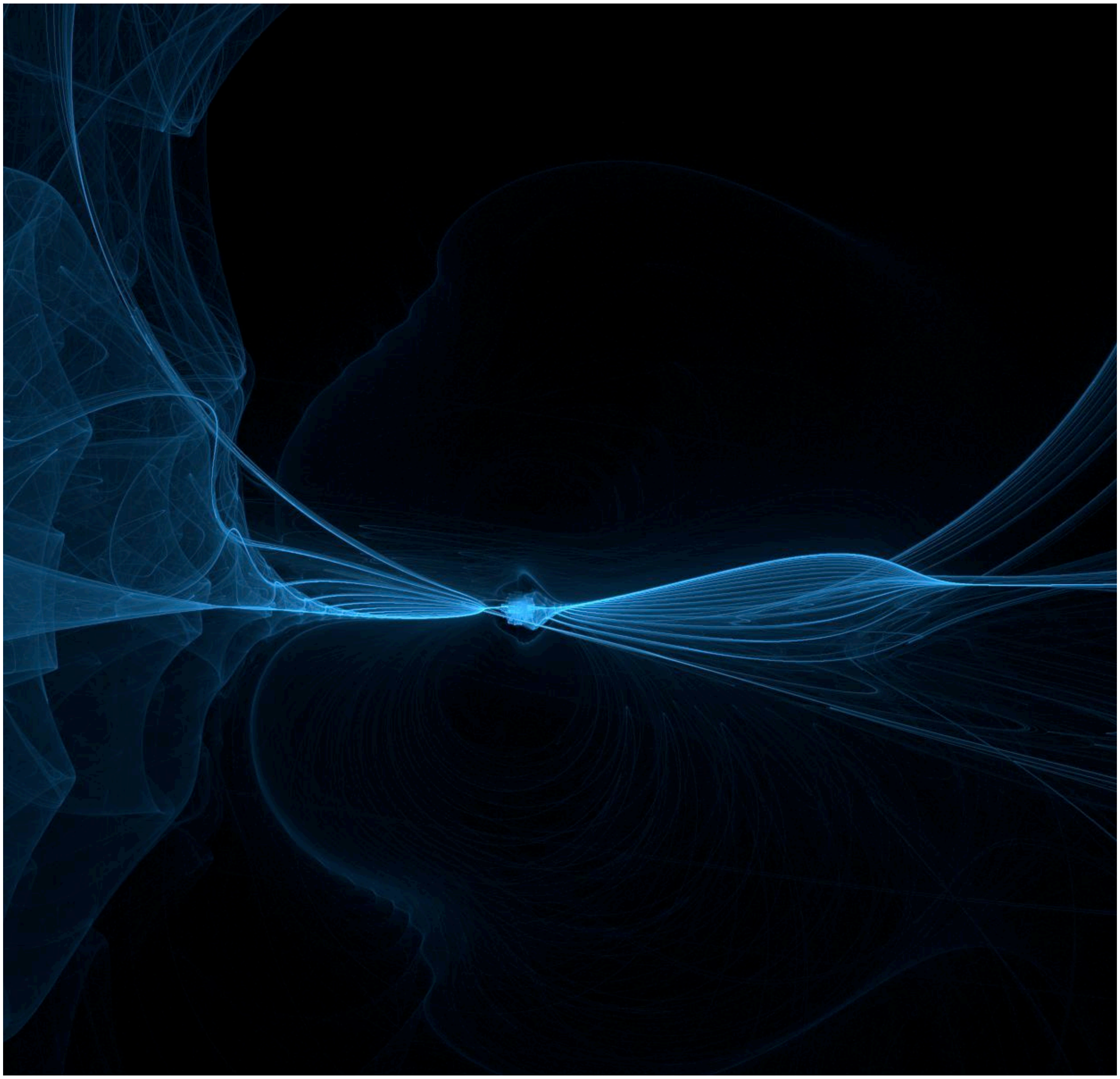
Sincerely yours,

Prof. Yaneer Bar-Yam
President

About NECSI

The New England Complex Systems Institute (NECSI) is an independent academic research and educational institution with students, postdoctoral fellows, and faculty. In addition to the in-house research team, NECSI has co-faculty, students and affiliates from MIT, Harvard, Brandeis, and other universities nationally and internationally.

NECSI has been instrumental in the development of complex systems science and its application to real world problems, including social policy matters. NECSI conducts classes, seminars, and conferences to assist students, faculty, and professionals in their understanding of complex systems. NECSI sponsors postdoctoral fellows, provides research resources online, and hosts the International Conference on Complex Systems.



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NECSI scientists consider the nature of human extinction and how we might avoid it.

News Update

A Growing Burden. Studies have already predicted that there will be a shortfall of physicians in the healthcare system by the year 2020. These studies estimate the shortfall to be anywhere between 51,000 to 228,000 physicians.

Healthcare workforce unable to grow sufficiently for preventive needs

According to the Partnership for Prevention, 100,000 lives could be saved each year if five preventive health care services were provided to 90% of the US population. However, a forthcoming report released by The New England Complex Systems Institute estimates that in order to provide this level of preventive service, the health care industry would be required to add 350,000 new full-time personnel. The study also estimates that the number of physicians would be required to jump by 50%.

"Clearly we need to concentrate more on preventive healthcare. The benefits are impossible to ignore," said Dr. Yaneer Bar-Yam, a researcher on the study. "But if we continue to use the current health care system as is, it will be very difficult to provide enough manpower to accomplish it any time in the near future."

Other studies have already predicted that there will be a shortfall of physicians in the healthcare system by the year 2020. These studies estimate the shortfall to be anywhere between 51,000 to 228,000 physicians. The

More Healthcare Research Available @

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Interesting Fact

2008

50 Million Americans do not have access to a primary care provider.

NECSI report, however, estimates it could be even worse due to implementation mandatory health care legislation in the near future.

"If our health care system suddenly has to provide service to the 15.9% of Americans who are currently uninsured, that's going to add a major burden," said Dr. Dion Harmon, researcher.

In order to meet the Partnership for Prevention's requirements, the report notes that the largest area of growth will be in information sessions, particularly counseling for obesity, diabetes, diet for high cholesterol, and tobacco cessation.

How evolution can help the flight delay problem

With airline delays worse than ever in the past year, officials at every level have called for the Federal Aviation Administration to do something about overbooked airlines. According to The Bureau of Transportation Statistics, nearly 30% of flights are delayed. As a result, officials such as Sen. Schumer (D-NY) have demanded the FAA update air traffic control technology to deal with the ever-increasing number of flights.

However, a group of scientists at The New England Complex Systems Institute warn that complex systems engineering, or, as it is sometimes called, "enlightened evolutionary engineering" is the only safe way to do so.

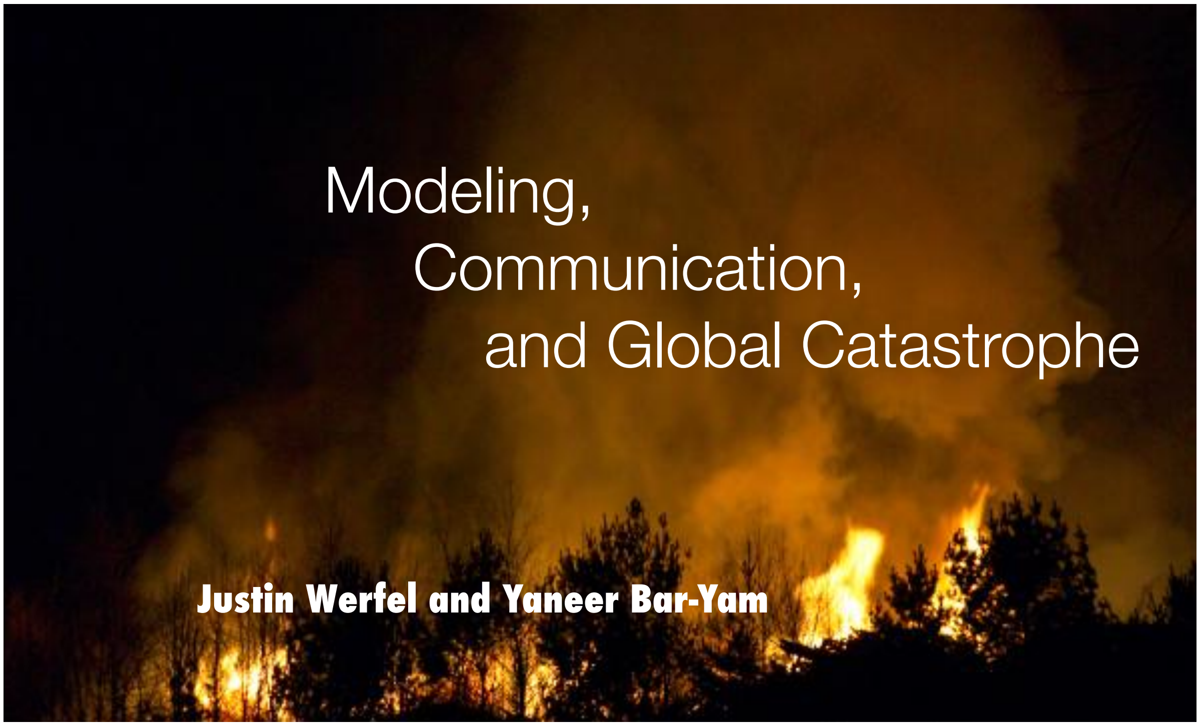
"What many people don't realize is that there already was a major attempt to update the air traffic control system from 1982 to 1994," said NECSI President, Dr. Yaneer Bar-Yam. "It was called The Advanced Automation System (AAS) and though it cost $3-6 billion dollars, the project was a complete failure. Not a single change from the project was actually implemented. The whole thing was scrapped."
NECSI scientists say that the AAS failed for a number of reasons, but the most significant was the decision to plan a "big bang" change that would transform the system from old to new in a very short time.

Air Traffic. Increased air traffic leads to increased delays.

"Many people blame the safety veto exercised by air traffic controllers, who can refuse any changes because of safety concerns," Bar-Yam said. "Therefore the only way to ensure safety when introducing new technology is redundancy, a concept fundamental to evolutionary engineering."

According to NECSI "evolutionary engineering" pits new technology against old, similar to what occurs in evolution. Any time new technology is introduced, the old technology is kept as well, both operating at the same time to see what performs best. Consequently, tried and true technology will always be available until new technology can be proven safe.

"These systems are too complex for new technology to be effectively tested before implementation," said Bar-Yam. "They have many interdependent parts and changing one piece affects the entire system, causing unanticipated collective results. This is why evolutionary engineering must be used. So we can safely test these items in the field, under real conditions."



Modeling, Communication, and Global Catastrophe

Justin Werfel and Yaneer Bar-Yam

Engaging with the future to be certain we have one.

It's no secret that the way we treat the planet may be putting us in danger. Global warming, fossil-fuel depletion, exhaustion of fresh-water supplies, and other issues are familiar matters of increasing public concern. But while attention may be on these issues for the moment—and may have been on them, off and on, for decades—human nature seems to limit our attention spans, and the continued fact of our not dying can make it hard to focus on such issues for long.

Recently, the two of us, researchers at the New England Complex Systems Institute in Cambridge, Massachusetts, became concerned about resource exhaustion for a novel reason. In 2004 we were finishing work on the evolution of altruism. Our computer models showed that limiting resource use was an evolutionarily successful thing to do, because simulated organisms that selfishly used all the resources they could get—in other words, selfish agents—thrived in the short term but left insufficient resources for later generations to survive. Selfish overexploiters would eventually go extinct, while altruists that cooperated to limit their consumption in a sustainable way survived indefinitely. The trick was that the model allowed selfish and altruistic strains to become physically separated from one another. That let selfish types take over a limited area, overuse its resources, and die out locally, while other strains survived elsewhere. But if the two types were kept mixed, then the selfish ones' short-term advantage let them outcompete the altruists, consumption spiraled out of control, and before long the entire species went extinct.

With these experiments coloring our vision, globalization and increasingly urgent issues of global resource exhaustion took on new meaning. It started to look like we were approaching in real life the well-mixed scenario, where the model turns from sustainability to global extinction. Reports of real-life global resource depletion seemed to show us well on the way to that outcome. At first, we took comfort in the thought that humans' cognitive powers should let us recognize impending danger (certainly plenty of people had sounded alarms about the environment) and might help us act to avoid catastrophe. But evidence from studies of many vanished human societies soon made it clear that we couldn't count on such an escape. And with the increasing interconnectedness of the modern world, the risk—and, models suggest, the likelihood—is global catastrophe.

Survival of our civilization will require two great human abilities. The first is the power to create models of the world—letting us understand our situation and predict its future, without needing to encounter a disaster to know that one is coming. The second is the power to communicate with each other to coordinate our actions, enabling the global response that a global problem demands. Our studies strongly suggest that communication—humans' ability to speak, write, and educate—is powerful enough to help us avoid extinction if we use it well. To that end, we've written this article to describe the situation in greater detail and explain what humanity's near-term choices may put at stake.

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Increased traffic contributes to global resource exhaustion

In his recent book *Collapse: How Societies Choose to Fail or Succeed,* Jared Diamond expertly details several examples of vanished human societies. These include the people of Easter Island, the inhabitants of Pitcairn and nearby Pacific islands, the Maya of Mexico and Central America, and the Norse settlement in Greenland, examples that we'll summarize briefly. In each case, the way people managed their environment led to resource exhaustion like deforestation, erosion, and water depletion or contamination—frequently at the same time as rapid population growth. Each time, the result was an environment unable to support its human population, so that the population fell to a fraction of its previous size and development, or died out altogether.

Easter Island has long been the favorite example of a society whose mistreatment of its environment led to its own destruction. Before human settlement, the island was covered with trees, including a type of palm tree that until its extinction was the largest in the world; it was also the richest breeding site for birds in Polynesia. After people arrived, in the company of chickens and rats, a number of things happened. Every large tree on the island was cut down; all of the native tree species went extinct. In fact, the first European ship to reach the island found no vegetation over three meters tall, and from a distance (as explorer Jacob Roggeveen wrote) "considered the … island as sandy, the reason … [being] that we counted as sand the withered grass, hay, or other scorched and burnt vegetation, because its wasted appearance could give no other impression than of a singular poverty and barrenness." Every land bird on the island went extinct, and nearly every seabird stopped nesting there, as a result of deforestation, overhunting, and predation by rats. Most sources of wild food were destroyed, and at the same time crop yields plummeted, due to factors like soil erosion and dessication that followed from the deforestation. The humans' diet, based on evidence from garbage heaps, went from mostly porpoises, birds, and open-ocean fish to inshore fish and rats. The result was widespread starvation. The population crashed by about 70%, the survivors took up cannibalism, there were civil wars, and the social order was overthrown, as were all the moai, the huge statues the island is famous for. The Europeans found a population so reduced in both number and circumstance that it was considered impossible for them to have been capable of erecting the moai—thus the familiar "mystery," still popular today, about what other advanced civilization or alien visitors must have been responsible.

Another Polynesian island example is the trio of Mangareva, Pitcairn, and Henderson Islands. At their peak, the three maintained an effective trade triangle: Mangareva lacked high-quality stone for tools, Pitcairn had such stone but was too small to support a self-sufficient human population, and Henderson was an excellent hunting ground but lacked necessities like fresh water. Collectively they were able to support a high standard of living for human populations on all three islands. Then, as on Easter Island, Mangareva suffered deforestation, soil erosion, extinctions of native species, and a population that grew beyond what the island could support. Without enough even for themselves, much less surpluses for export, the Mangarevans ceased trade, and imports of the resources they needed stopped. There followed, again, civil war, cannibalism, and in the end a much smaller population that held on with a drastically reduced standard of living. Meanwhile, on Pitcairn and Henderson, without the importation of necessities, the populations used up their remaining resources all the faster, until everyone on both islands was dead. Diamond points to these islands as an example of an interconnected culture that broke down catastrophically when one crucial part of it, and its connections to other parts, failed.

Island examples are useful for illustration, but not all such collapses have occurred among isolated societies in fragile environments. Another example is that of the Maya—arguably the most advanced society in the pre-Columbian Americas, occupying a region that was ecologically fairly robust. After the year 800, 90 to 99 percent of the Maya disappeared, in what's called the Classic Maya collapse. Diamond focuses on the Copán Valley, an agriculturally rich area where farmers cut down trees extensively for fuel, construction, and plaster, and to clear fields. The resulting erosion made it impossible to farm on the mountainsides, and also swept the less-fertile mountain soil down over the valley soil. Large-scale deforestation also tends to reduce rainfall, because of the role trees play in the water cycle. Crop yields fell just as the population was increasing sharply. The result was internecine fighting, the overthrow of the local king, and the burning of the palace, and eventually the human population of the valley disappeared. Similar factors contributed to the fall of the more widely spread Maya civilization.

Unfortunately, the course we're on is far from sustainable—not just in the long term, but even in the short term. The end of the road is coming very quickly if nothing changes.

One last example—a story familiar by this point. The Norse in Greenland cut both trees and turf, for construction and fuel. The loss of trees, and the damage to vegetation caused by their herd animals, led to soil erosion. The erosion and turf-cutting reduced the acreage of pasture and farmland available. Eventually there was too little pasture to support enough animals to breed back the annual losses. Those settlers not able to escape on ships starved and froze to death. Again, a society that overused its resources rendered its environment unlivable and ultimately disappeared.

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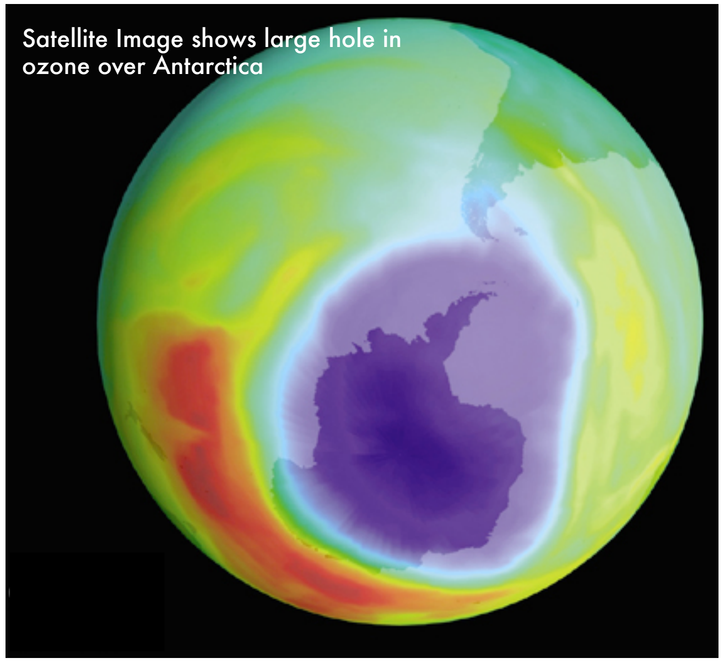
The lesson of these case studies is that, like other evolving species, humans can bring about their own end. This makes it all the more vital to ask: How are we doing in stewardship of global resources?

Unfortunately, the course we're on is far from sustainable—not just in the long term, but even in the short term. The end of the road is coming very quickly if nothing changes.

This forecast is reflected in the United Nations–sponsored Millennium Ecosystem Assessment, completed in 2005 and representing the work of more than 1,300 scientists from around the world. Its conclusions were grim: *"Human actions are depleting Earth's natural capital, putting such strain on the environment that the ability of the planet's ecosystems to sustain* *future generations can no longer be taken for granted."*

Note well that this statement doesn't refer to any single country or ecosystem. The system at risk is our entire planet. In today's world of globalization and interconnection, the fate of every community in the world is increasingly tied with that of every other. The resource-depletion issues the world now faces—dwindling fossil fuel reserves, overextended freshwater supplies, widespread pollution, atmospheric degradation, overfishing, deforestation, severely damaged farmland—are increasingly worldwide ones.

We are approaching the peak of availability of crude oil supplies, if we haven't passed it already; reserves of oil and natural gas are expected to last another few decades, beyond which extraction will be more and more expensive and damaging to the environment. We're using most of Earth's fresh water supplies now, and depleting aquifers worldwide faster than they're replenished. Air and water pollution are estimated to kill several million people each year, and toxic chemicals released into the environment affect populations thousands of miles away from their manufacture and use. Twenty percent or more of the world's population depends on seafood as its main protein source, and more than 70 percent of the world's fish species are estimated to be either fully exploited or depleted. Half the planet's historic forests have now been cut down, and the rate of deforestation is increasing. Somewhere between 20 and 80 percent of all farmland is considered severely damaged, and erosion and other factors are eliminating usable soil many times faster than it's naturally restored.



Satellite Image shows large hole in ozone over Antarctica

Diamond makes the critical point: "Because we are rapidly advancing along this non-sustainable course, the world's environmental problems *will* get resolved, in one way or another, within the lifetimes of the children and young adults alive today. The only question is whether they will become resolved in pleasant ways of our own choice, or in unpleasant ways not of our choice, such as warfare, genocide, starvation, disease epidemics, and collapses of societies." The interconnection of our world means that these "unpleasant" resolutions will be global in scale.

With the risk of such catastrophe at hand, we need to ask the second vital question: What is the United States, as a leading political and economic superpower, doing in response to the state of the world and the direction in which it's headed?

Unfortunately again, the track record for at least the last several years has been anything but reassuring. This is not simply an issue of making poor choices; rather, our leaders' decisions reflect a dangerous inversion of the decision-making process. One might think that a sensible way to decide policy would be to collect evidence about a situation, then base a decision on that evidence. Yet the pattern repeatedly demonstrated by the federal government has been just the opposite: to decide on a course of action based on short-term political, economic, or ideological considerations, and then find evidence supporting that decision afterward, ignoring anything to the contrary.

Examples of this pattern reported in major news sources are depressingly easy to find. Within the span of a couple of months in 2005, a few such stories included the following:

- In response to new evidence for human contributions to global warming presented at the annual meeting of the American Association for the Advancement of Science, a spokesman for the Bush administration stated that its position—that the science of climate change is uncertain—was unaffected by the new work, adding, "Our position has been the same for a long time." ("New global warming evidence presented—Scientists say their observations prove industry is to blame," *San Francisco Chronicle*, 2/19/2005).

- A survey of U.S. Fish and Wildlife Service scientists found that very many reported having been directed to change or discard their findings, for political reasons. ("Endangered Science?," *Science*, 2/9/2005).
- Government climate reports were repeatedly altered to downplay evidence that greenhouse gases contribute to global warming, by a White House political appointee whose previous job had been "climate team leader" and lobbyist for the American Petroleum Institute. ("Bush Aide Edited Climate Reports," *New York Times*, 6/8/2005).
- Before relaxing restrictions on cattle grazing on public lands, the administration made fundamental changes to an analysis of the environmental impact of such grazing—for instance, removing a statement that the grazing would have a "significant adverse impact" on wildlife and adding one saying that the new rules would be "beneficial to animals." ("Land Study on Grazing Denounced," *Los Angeles Times*, 6/18/2005).
- The EPA released a new rule about mercury emissions from power plants, saying that stronger restrictions would cost far more than the benefits they conferred—but suppressing a study they themselves had funded, co-authored, and reviewed, which had found just the opposite. ("New EPA Mercury Rule Omits Conflicting Data," *Washington Post*, 3/22/2005).

This politicization of science is deeply dangerous. Not only does it undermine the nature and value of science, but it has the potential to lead us into catastrophe, by undermining our capacity to avoid it.

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We do have such a capacity. The key is in our ability to make models of the world, to use them to understand likely futures and—assuming we choose to do so—modify our behavior accordingly.

The ability to use models to understand and shape the future is a powerful step beyond our ability to learn from the past. It allows us to learn from actions we haven't actually taken. By letting us anticipate rather than experience the consequences of our decisions, it gives us an invaluable tool for survival, qualitatively different from forms of learning based only on past events.

Let us digress for a moment to think about ways that learning from the past takes place. At the lowest level is evolutionary learning. Imagine a population of prehistoric humans living in a forest with colorful, deadly mushrooms. Some of these humans, through natural variation, happen to have an innate fear of colorful mushrooms, while others are perfectly willing to eat them. The latter die, poisoned, while the rest survive to produce more mushroom-averse offspring. After a few generations of this process, the population as a whole can be said to have learned to avoid poisonous mushrooms.

This process shapes the evolution of single-celled creatures as much as it does ours. More complex animals also have the capacity for higher, faster forms of learning. Suppose that in the same forest spotted mushrooms grow that are only mildly poisonous. A single human being might eat one of these, get sick, associate the illness with the meal, and avoid spotted mushrooms for the rest of his life. Such learning through personal experience operates on an ecological, rather than evolutionary, time scale, allowing an individual to adapt without dying.

A still higher and faster level is social learning, learning through shared experience. By communicating through language and using cultural transmission, one member of the population can warn others about her bad experience with a spotted mushroom, and the rest can thereafter avoid that danger without having to suffer it themselves.

All three levels of learning depend crucially on an experience's not being *too* fatal. The mechanism of evolutionary learning, for example, requires that some members of the population survive to avoid mushrooms in the future; it's no good if everyone dies and the population goes extinct.

This issue suggests an important point about the way evolution works. Selection can act on individuals, killing single organisms; or it can act on higher levels, where a group of related individuals is wiped out together. The latter could happen, for instance, if the people of one tribe never learn to avoid the deadly mushrooms and all end up dying from them. Later, a tribe from a different region might move into that now-depopulated part of the forest. As long as some members of the species survive in remote subpopulations, local extinctions can shape the course of evolution without being fatal for the entire species.

The extent of the role played in evolution by selection above the level of individuals has been controversial for decades, and remains so today. But growing evidence from a variety of models suggests that that mechanism has important effects in a wide range of circumstances, and can help explain puzzles like the prevalence in nature of altruism—a phenomenon that biologists have long argued is illusory or, at best, favored by evolution only under unusual circumstances.

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We've used computer simulations to study such models in an effort to better understand how evolution works. It turns out to be easy for local extinctions of similar individuals to arise naturally in the models, without needing to be explicitly included, and for this mechanism to lead to an overall moderation of resource exploitation. The unfortunate implications of these results for the current global situation will become clear.

Consider a predator-prey system in a large space divided into many regions. Each region can be empty, or populated by the prey species, or populated by both predators and prey; predators cannot live in a region without prey. As time passes, prey can reproduce, spreading to nearby empty regions; predators can likewise reproduce, spreading into nearby regions with prey. Predators in a region can kill off all the prey available in that region—leaving nothing for themselves to live on and thereby causing their own deaths.

For this discussion, we'll hold two rates in the model constant: the prey reproduction rate, and the rate at which predators kill off prey. The predator reproduction rate, however, will be allowed to evolve. That is, the predators in any one region have a fixed probability of spreading to nearby regions, but if they do, their offspring in the neighboring region may have a slightly higher or lower reproduction rate.

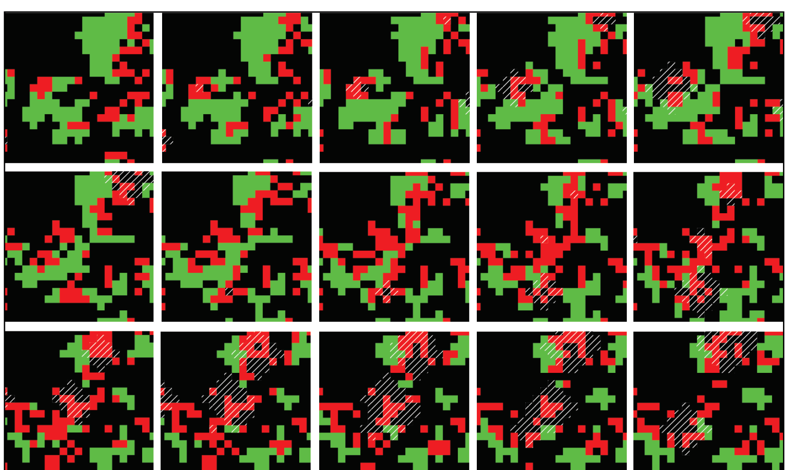

Figure 1. Snapshots of a small area of the predator-prey model, as time passes (leftto right, then top to bottom), showing the spread and death of predators and prey. Black regions are empty, green ones are populated by prey, red ones by both predators and prey. The striped overlay shows the signal sent out by predators experiencing crowding; it spreads to some distance, then fades. (*Image from J.K. Werfel and Y. Bar-Yam, PNAS 101, 2004.)*

Initializing this model at random and letting it run produces a cyclical, patchy process: large-scale patches of empty space are invaded by patches of prey, which are invaded in turn by patches of predators, which give way once more to empty space. The process is self-organizing: if the fixed prey reproduction rate or predator kill rate is changed, the predator reproduction rate will evolve to restore the patchy structure.

What happens to the predator reproduction rate over time in this scenario? The traditional, individual-centered view of evolution— "survival of the fittest," where "fittest" explicitly means producing the most offspring—would predict that faster-reproducing predators should always have the advantage, and so the reproduction rate in the predator population should continually increase. However, what actually happens in the model is that the average reproduction rate comes to settle at some limited equilibrium value. If the system starts with a lower average value, the rate will increase until it reaches that equilibrium; if the initial reproduction rate is higher, the average in the population will fall to that stable value. That is, the successful predators aren't the ones that reproduce as fast as possible. On the contrary, the successful predators are the ones that limit their reproduction—each giving up an immediate reproductive benefit to itself, a form of altruism.

What makes such a counterintuitive result possible? The answer is a combination of overexploitation and local extinctions. It's true that a faster-reproducing region of predators has an advantage over a slower-reproducing one—locally. But at the same time, all predators are killing off prey; and if their rapid reproduction leads them to use up their available resources faster than those are being replenished, that patch of predators will perish. Later, prey will move in to repopulate that now-empty space, and then surviving, slower-reproducing predators can follow.

Readers aware of the group selection controversy in evolutionary biology may be reassured to know that in this model, there are no explicit groups of predators being pitted against one another. Boundaries between patches are fluid, and predators may be part of one patch one moment and a different patch the next. The key is that, because reproduction occurs locally, predators near each other will tend to have similar reproduction rates. Meanwhile, local extinctions are more likely to occur for patches of faster-reproducing predators. The result over the long term is selection pressure against faster reproduction, even while short-term selection pressure favors faster reproduction.

The same model can be used to describe a system of hosts and pathogens, of plants and herbivores, or any other ecology where one species lives at the expense of another. The crucial elements in the model are, first, that there is a necessary resource that can be both exhausted and renewed; and, second, that the model has spatial extent. Both, of course, are typical features of the real world. Details, large and small, of such models can be varied widely, but the qualitative behavior holds over a great range of conditions. The generic result is a limit to how fast resources are used up, actively maintained by local overexploitation and consequent local extinctions.

Crucially, for a *well-mixed* model—that is, one without a sense of locality, where predators can reproduce to attack any prey, not just those nearby—the behavior is very different. In such a case, there can be no selective pressure against faster reproduction. Instead, predators keep reproducing faster and faster, until the result is extinction *everywhere*. Again, that generic result, increasing exploitation followed by global extinction, holds across many ways of varying the model, so long as it is well-mixed.

Once more, the evidence from history is that the principle of long-term species survival through repeated local extinctions holds no less for humans than it does for other organisms. Further, with the ongoing rise of globalization, our world is approaching a well-mixed system, each region connected to every other. Models show that the outcome for such a system is universal extinction—but are we doomed to that outcome? Or is there a way out?

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The ability to communicate is central in our capacity to choose a future. Coordinating our behavior is key. It does no good for one person to try to live sustainably if a billion others are exploiting all they can for short-term personal gain.

Suppose we introduce a communication mechanism into the model described above. Crowding, in nature, often leads to changes in behavior. A (relatively) simple example is given by the "quorum-sensing" molecules that many bacteria secrete. If the density of bacteria becomes great enough, so that the concentration of these molecules exceeds a given threshold, the bacteria will start to behave differently—for instance, producing a metabolically costly enzyme that allows them to collectively take advantage of a food source that would remain inaccessible if their density were too low. With this sort of observation in mind as an example, we introduce into our model a signal linked to crowding. Specifically, when a region of predators is surrounded on all sides by other regions of predators, the surrounded region sends out a transient signal that spreads to nearby regions. (Once again, the details of how this signaling works in the model don't matter to the results.) Predators in the model are now given a second heritable trait, "response," which describes a temporary change to their reproductive rate when in the presence of the signal. That response may be to reproduce faster or slower. As with reproduction rate, the response to signal is constant for any given region of predators, but may be different in offspring regions.

The ability to communicate is central in our capacity to choose a future.

Traditional, individual-level selection would again predict that faster reproduction in response to the signal should be favored. As available resources are depleted, there should be increasing pressure to grab the last of them, granting a competitive advantage over neighbors who might otherwise get there first. However, what actually proves to be the successful strategy in this model is, again, restraint. Far from reproducing more quickly, predators evolve to drastically slow their reproduction when they detect the crowding signal. The mechanism is the same as before: a short-term local advantage is of little use if the whole patch of predators dies from overexploitation shortly afterward.

It's important to note that the predators signaling are not those restraining their reproduction. The signaling predators are surrounded and have no further chance to reproduce; they're like the old man in the story who plants a carob tree he will never see grow, in order to benefit later generations. Conversely, non-signaling predators are on the front lines of unexploited regions of prey. As far as they can see, there's plenty of room for continued growth, and no reason not to take advantage of it. However, if they respond to the crowding signal by not taking advantage of apparent resources, the population has a much better chance of avoiding extinction.

"Invasion" experiments measure the competitive advantage of one type of predator over another. For instance, take an environment populated by predators that signal when surrounded, but have no reproductive response to that signal; and introduce a single predator whose offspring do have the heritable trait of response to the signal. The chance of a responsive invader of this sort ultimately taking over the population—its descendants entirely eliminating the descendants of the original, invaded population—is many times greater than the chance of a non-responsive invader taking over a non-responsive population, or a responsive invader taking over a responsive population. This result from the model shows that the capacity for response—that is, the ability for real communication—confers a significant advantage for survival.

Taking action: Volunteers participate in a beach clean up.

The opposite invasion experiment addresses classic objections to the evolutionary feasibility of altruism. The argument is that altruism should be unstable, because "cheaters"—those who ignore the community convention of collective self-sacrifice (in this context, predators who do not restrain their reproduction in response to the signal)—should always have an advantage over altruists. Similarly, "manipulators"—here, those whose signaling induces others to restrict reproduction, while they themselves exhibit no such restraint—should have a competitive advantage. To experimentally investigate these concerns, we performed simulation experiments introducing a non-responsive invader into a responsive population. And the result? In over 140,000 trials, we found not one successful invasion. In these experiments, the local advantage gained by cheaters and manipulators is never enough to allow them to take over the global population.

These simple models demonstrate, then, that communication can be a powerful tool in letting populations avoid extinction. This power helps explain why within-species communication is so universal throughout nature, ubiquitous in organisms from blue whales all the way down to bacteria. For us as well, anticipating disaster and taking steps to avoid it—even if those steps appear to be against our immediate, individual self-interest—is both possible and crucial. The importance of action is all the greater in an increasingly well-mixed world. By recognizing danger, signaling this danger, and collectively responding, we can improve our chances of survival. Each of these three elements is crucial; without any one of them, the other two are useless. The most pressing need today is for the third. Scientific models have recognized the dangers we face as a species, and many researchers and public figures have worked to make this information widely known, but whether effective global response will follow is still very much in question.

We should recognize that it's very unlikely that humanity would go extinct all at once in any real scenario. Before that point, the mechanisms we've built up to connect the world so tightly would break down; our global society would fragment into many less-connected, more primitive regions, each free to undergo its own catastrophes independently. Many such groups, through fortune of circumstance, would survive, albeit not with what we think of as our level of civilization and modern standard of living. So the risk is not that we lose everything—only most of what we feel is important, the culture, knowledge, and way of life that we have struggled to build and refine in the modern era.

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It's clear enough what lessons we might draw from all this. We've seen that the pattern of local overexploitation and extinction is pervasive in nature and in history, that we appear well on the way to triggering such a fate in the foreseeable future, and that the world has become connected enough that the results of such a collapse will be felt worldwide.

It's much less clear what lessons we will actually draw. Our recent record of choosing to address problems, rather than choosing to ignore them, is poor. But our abilities to anticipate disaster, and to cooperate to avoid it, can be of no help if we don't use them.

Modeling can be a very powerful tool if we take advantage of it. It represents a huge step forward from the three forms of learning discussed earlier (evolutionary, personal, and social), with an important qualitative difference: while those other forms rely on the occurrence of negative events, modeling can predict such events before they happen, and so keep them from happening at all. In situations unprecedented in history, as with the increasingly pervasive interconnection associated with globalization, that's a crucial feature.

Both learning and modeling make it possible to avoid disaster—learning by remembering the past, modeling by predicting the future. Yet neither tool is of any help unless it leads to changes in behavior. We can use the best tools available to us—scientific studies that forecast what will happen, based on what we know about how the world works and what has occurred in the past—to recognize the risks in each course of action and proceed accordingly. Or we can move blindly forward and accept whatever comes.

Early in this article, we gave examples of well-known environmental problems, each an issue of overusing or damaging a global resource. Others before us have warned about these and other specific dangers and have proposed detailed actions that the people of the world might take in response. Our goal here is not to repeat their efforts. Rather, we want to emphasize the scope of these dangers—that it's not merely isolated communities that are threatened, but in a very real sense, the world as we know it—to help spur the sense of urgency necessary for humanity, individually and collectively, to respond.

In some ways, the picture may be less bleak than it sounds. Collapse is not inevitable for human societies. In his book, Diamond also describes success stories—on Tikopia Island and in 17th-century Japan and the Viking settlement in Iceland, people recognized impending disaster and successfully took steps to avoid it, leading to sustainable societies that have persisted for hundreds to thousands of years. In our own case, responding to the federal government's unwillingness to recognize or act on environmental problems, businesses as well as state and local governments have taken steps to address issues such as greenhouse gas emissions on their own. And the public recognition of one major issue, climate change, has recently increased to an extent that seemed unthinkable only a few years ago.

Action is possible, and action is being taken. Yet it is only through concerted and sustained effort that we can solve global problems. Our sincere hope is that the need for action, and the risks of inaction, will become increasingly widely known and accepted. Then we as a global society will be ready to accept small, short-term sacrifices for the sake of a sustainable future.

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