Kates, R. W. and W. C. Clark, 1996. "Environmental Surprise: Expecting the Unexpected," Environment, Vol. 38, No. 2, pp. 6-11, 28-34.

environmental surprise

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By Robert W. Kates and William C. Clark

CENTERS FOR DISEASE CONTROL AND PREVENTION

The most memorable events are frequently the most surprising ones; indeed, surprises may be the most influential events of any era. This is certainly true of the environmental surprises of the past 25 years and those that we can anticipate over the next 25 years. Anticipate? Although, by definition, genuine surprises are always unanticipated (at least by most of us), surprise as a phenomenon is surely to be expected. In fact, in one well-developed and empirically supported theory, surprise is an inevitable consequence of the interactions between humans and their environments (see the box on page 8). This final article in *Environment*'s Earth Day series explores the environmental surprises of the recent past and those yet to come. It speculates on ways of anticipating and responding to surprise—indeed, of using it creatively to sustain human use of the Earth.

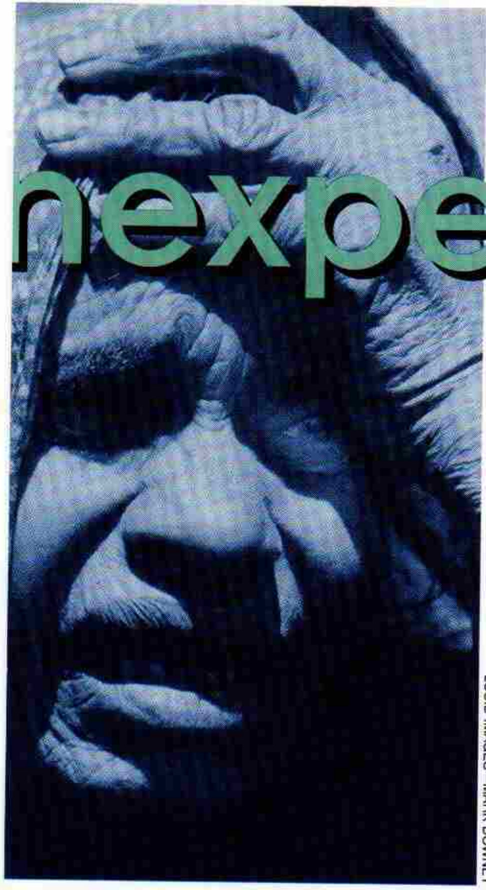
Environmental Surprises Since 1970

To put the issue in perspective, it will be useful to examine three major environmental surprises of the last 25 years: Legionnaire's disease, the Bhopal disaster, and the depletion of the stratospheric ozone layer.

Legionnaire's Disease

In July 1976, in celebration of the 200th anniversary of the Declaration of Independence, the American Legion held its national convention in Philadelphia. The legacy of that convention, however, was a new, sometimes fatal, disease characterized by high fever, dry cough, lung congestion, and subsequent pneumonia and liver and kidney damage. Altogether, Legionnaire's disease struck 182 attendees of the convention, 29 of whom died. For months, doctors, epidemiologists, and scientists struggled to find a cause for the illness. Finally, through the work of a very persistent investigator, it became clear that the disease was caused by several strains of a bacterium called *Legionella pneumophila* that was first identified 29 years earlier. The outbreak apparently occurred because water vapor containing this bacterium was transmitted through the hotel's air conditioning ducts.[1] Legionnaire's disease would be the first in a series of infectious diseases to appear or reappear in the late 20th century.

Legionnaire's disease was the product both of a unique environment (an air conditioning system) and the technology that created that environment. The list of surprise diseases with an environmental or technological component also includes toxic shock syn-



LUCID IMAGES—MARK DOWNEY

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THE FINAL ARTICLE IN THE EARTH DAY SERIES

drome (caused by a super-absorbent tampon) and Lyme disease (caused by the changing ecology of suburban living, reforestation, and growing deer populations). Other environmental factors include increased travel and the globalization of the food supply, which have exposed residents of temperate zones to tropical diseases and promoted the spread of food-borne diseases. Furthermore, population growth itself might encourage the proliferation of new infectious diseases because, as the number of people increases, there is a larger reservoir of hosts in which viruses may proliferate. Combined with the evolution of drug resistance and increased immune system deficiencies, modern industrialized societies that thought themselves invulnerable to infectious disease must now cope with its surprising recurrence.

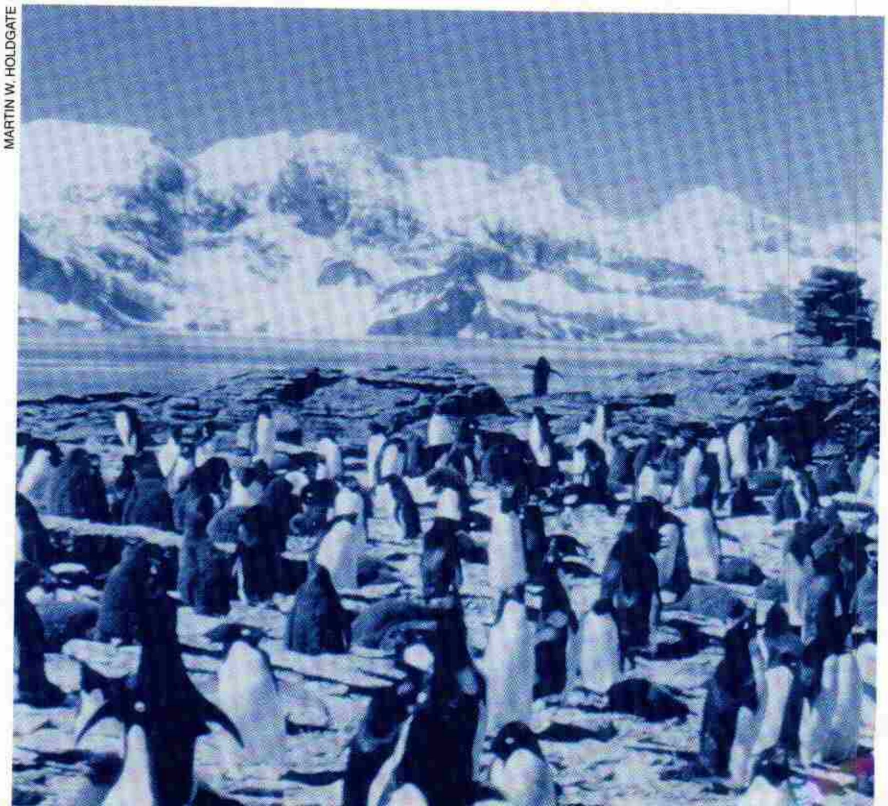
Bhopal

Bhopal is a city in central India of about 1 million people where Union Carbide, a U.S. chemical company, had a pesticide manufacturing plant. On 3 December 1984, an unexpected chemical reaction took place in a storage tank of methyl isocyanate, a toxic gas used in the production process. The runaway reaction released a great deal of heat and vaporized between 30 and 40 tons of the gas, which spread over some 30 square miles, killing thousands and injuring hundreds of thousands of people.[2]

A series of human errors and equipment failures created the chemical reaction. First, large amounts of water (approximately 120–240 gallons), which generated the heat needed to initiate the subsequent reactions, entered the tank when a hose was mistakenly attached to a pressure gauge. Second, as a result of the distilling process, there was an abnormally high level of chloroform present; this increased the corrosion of the tank, providing more iron as a catalyst for the reaction. Further human and mechanical errors allowed the gas to escape. A refrigeration system that should have cooled the tank had been inoperative for six months. The vent-gas scrubber and flare, safety equipment designed to destroy contaminated methyl isocyanate and vent gases, were also not fully operational. The water-spray system failed to contain the escaping gas. And finally, the Bhopal community had no emergency plan. Much of this may be attributable to the complacency of local management, who were apparently lulled by the knowledge that the plant had one of the best safety records in India.[3]

There was also little oversight or regulation. The government of the state of Madhya Pradesh had never mandated safety standards for the plant and lacked the technical and institutional capacity to implement toxic chemical control laws. (This

MARTIN W. HOLDGATE



A THEORY OF SURPRISE

The pioneering work on surprise in environmental systems was done by Canadian ecologist C. S. Holling in the early 1970s. Originally focused on episodes of discontinuous change arising in natural ecosystems, Holling's studies on surprise have expanded over the years to encompass a general perspective on the interactions of human institutions and the environment. They have exerted a substantial influence on others' ideas, including ours.

In Holling's view,

surprise concerns both the natural system and the people who seek to understand causes, to expect behaviors, and to achieve some defined purpose by action. Surprises occur when causes turn out to be sharply different than was conceived, when behaviors are profoundly unexpected, and when action produces a result opposite to that intended—in short, when perceived reality departs qualitatively from expectation.[1]

He emphasizes that our expectations are strongly shaped by underlying metaphors, models, and belief systems that rarely receive critical scrutiny. In his most recent work, Holling argues that four alternative beliefs about causality, stability, and change can be seen in contemporary efforts to address problems of environmental management and sustainable development. He caricatures them as follows:[2]

Nature Cornucopian is a belief in "smooth exponential growth, where resources are never scarce because human ingenuity always invents substitutes. . . . It assumes that humans have an infinite capacity to innovate and that nature changes gradually." Much of the work of Julian Simon and Herman Kahn reflects such beliefs.[3]

Nature Anarchic is a belief in a world "where increase is inevitably followed by decrease. It is a view of fundamental instability, where persistence is only possible in a decentralized system in which there are minimal demands on nature." Holling cites the writings of the late E. F. Schumacher as typical of this perspective.[4]

Nature Balanced is a view "of logistic growth, where the issue is how to navigate a looming and turbulent transition—demographic, economic, social, and environmental—to a sustained plateau." Holling associates this perspective with reformist individuals and institutions ranging from the Brundtland Commission to the International Institute for Applied Systems Analysis. It also characterizes much of the work done by the authors of this article.

Nature Resilient is a belief in a world "of nested cycles organized by fundamentally discontinuous events and processes. That is, there are periods of exponential change, of growing stasis and brittleness, or readjustment and collapse, and of reorganization for renewal." Holling puts his own work in this category but sees Harvey Brooks' work on technology, Brian Arthur's work on economic innovation, and William McNeill's view of history as being in the same spirit.[5]

Holling emphasizes that none of these belief systems is "right" or "wrong." Rather, each has been successfully applied to certain problems of environment and development and each has failed in other cases. More significantly, these belief systems entail radically different expectations about the interactions between people and environments and have therefore led their adherents to be surprised by very different things. Out of these surprises, at least for those who take them seriously, Holling sees a fifth caricature of reality emerging. This is Nature Evolving, a set of beliefs that is inherently "evolutionary and adaptive" and that draws insights and examples from a wide range of environmental and social systems. Holling identifies a number of generic features of the emerging view that transcend their diverse disciplinary origins and bear directly on contemporary problems of environmental management:[6]

The problems are essentially systems problems, where aspects of behavior are complex and unpredictable and where causes, although at times simple (when finally understood), are always multiple.

The problems have a fundamentally nonlinear cause. They demonstrate multistable states and discontinuous behavior in both time and space.

The problems are increasingly caused by slow changes, reflecting decadal accumulations of human influences on air and oceans and decadal to centurial transformations of landscapes. These slow changes cause sudden changes in fast environmental variables that directly affect the health of people, productivity of renewable resources, and vitality of societies.

The spatial span of connections is widening, so that the problems are now fundamentally cross-scale in both space and time.

Both the ecological and social components of these problems have an evolutionary character. That is why the phrase 'sustainable development' is not an oxymoron. The problems are therefore not amenable to solutions based on knowledge of small parts of the whole or on assumptions of constancy or stability of fundamental relationships—ecological, economic, or social. Assumptions that such constancy is the rule might give a comfortable sense of certainty, but it is spurious. Such assumptions produce policies and science that contribute to a pathology of rigid and unseeing institutions, increasingly vulnerable natural systems, and public dependencies.

Holling offers us a world of interacting nature and society that is stranger than we can know, where surprise is the rule and in which—surprisingly—this very unpredictability is a source less of despair than of hope.

1. C. S. Holling, "The Resilience of Terrestrial Ecosystems: Local Surprise and Global Change," in W. C. Clark and R. E. Munn, eds., *Sustainable Development of the Biosphere* (Cambridge, U.K.: Cambridge University Press, 1986), 292–317.

2. C. S. Holling, "What Barriers? What Bridges?" in L. H. Gunderson, C. S. Holling, and S. S. Light, eds., *Barriers and Bridges to the Renewal of Ecosystems and Institutions* (New York: Columbia University Press, 1995), 14–16.

3. See, for instance, J. L. Simon and H. Kahn, *The Resourceful Earth: A Response to Global 2000* (Oxford, U.K.: Basil Blackwell, 1984).

4. See E. F. Schumacher, *Small is Beautiful: Economics as if People Mattered* (New York: Harper and Row, 1973).

5. H. Brooks, "The Typology of Surprises in Technology, Institutions, and Development," in Clark and Munn, note 1 above; B. W. Arthur, "Competing Technologies, Increasing Returns, and Lock-in by Historical Events," *Economic Journal* 99 (1989): 116; and W. McNeill, *The Human Condition: An Ecological and Historical View* (Princeton, N.J.: Princeton University Press, 1979).

6. Holling, note 2 above, pages 33–34.

was a general problem, as surveys have shown that only 16 of the 50 pesticide manufacturing plants in India had significant pollution-control systems.) And Union Carbide, which owned about 49 percent of the Bhopal plant, failed to implement its own (i.e., U.S.) safety rules, apparently comfortable in the knowledge that it was not contravening Indian regulations.[4]

More than a decade later, much is still unknown about both the causes and the consequences of the accident. Some observers detected other cyanide releases after the accident, though these were officially denied. Only blindness and respiratory injuries have been studied, but many other ailments have been reported, including gastrointestinal, reproductive, neurological, and psychological ones. Union Carbide settled with the Indian government for $470 million, which was to satisfy an estimated 3,000 claims for death and 52,000 for injury. However, more than 16,000 claims for death and 600,000 for injury have been filed. To date, more than a decade after the accident, only about 80 percent of the death claims and 30 percent of the injury claims have been considered (and half of those have been rejected), and it is estimated that it will take another five years to consider them all.[5]

Ozone Depletion

Chlorofluorocarbons (CFCs) are a family of synthetic chemicals developed in 1928 to provide a safe alternative to the hazardous refrigerants of the day. The compounds then in use, such as ammonia, methyl chloride, and sulphur dioxide, were safe only as long as the equipment containing them was properly used and did not malfunction. But technological accidents were at least as common in the United States in the 1920s as they would prove to be in India in the 1980s. Methyl chloride, for example, killed more than 100 people in a Cleveland hospital in 1929 when it leaked into the ventilation system following an unrelated explosion in the x-ray lab. CFCs, in contrast, were nontoxic, nonflammable, noncorrosive, and cheap. They promptly took over the refrigerator market, helped to launch the fledgling air conditioning industry, and were eventually adopted as the propellant of choice in aerosol spray cans.[6]

By the early 1970s, the world was producing almost a billion kilograms of CFCs a year, with the amount doubling every five years. Then, in 1974, scientists Mario Molina and F. Sherwood Rowland published a technical paper hypothesizing that these same safe CFCs were slowly drifting up into the stratosphere and breaking down, releasing chlorine atoms that would lead to the destruction of stratospheric ozone. This, in turn, would allow ultraviolet radiation to penetrate to Earth, where it could cause a great deal of damage, including skin cancers.[7]

Urged on by activist scientists and a concerned Congress, U.S. media took the lead in spreading the alarm. They devoted an extraordinary amount of coverage to CFCs in 1975 and helped to fix inexorably in the public mind the image of frivolous spray cans blasting holes in the sky. The prospect of increased cancer risk lurked just offstage. Local political action and consumer boycotts against products containing CFC aerosols spread rapidly. By the time the U.S. government officially banned CFC propellants in 1978, the action was virtually superfluous: Domestic use had already fallen precipitously, solely on the basis of an as yet unproven hypothesis.

For the next 10 years, however, there was no further action on the CFC front. A decade after the initial surprise, the threat of ozone depletion had been all but forgotten by the media, politicians, and the public. After dropping somewhat, worldwide CFC production climbed back above its 1974 level. Society would require a second surprise—the discovery of a real, rather than a hypothesized, hole in the ozone layer in 1985—to put the issue back onto the public agenda and to push the world toward serious collective action on threats to stratospheric ozone.[8]

STILL PICTURES—ROB SCOTT

The lead in the paint peeling from these classroom walls in the United Kingdom represents a major unanticipated hazard.

Common Characteristics

The above cases illustrate four characteristics that environmental surprises have in common: They confound social expectations; they are not completely unpredictable; they are often harmful, injuring people or the environment; and they open windows of opportunity for increasing our capacity to manage environmental problems.

The essence of surprise is that it confounds our expectations, entailing events that we never thought of or imagined could occur. Legionnaire's disease was so surprising because of the widespread assumption that infectious diseases had been conquered in industrialized countries. And while fires and explosions were relatively common at chemical plants, the notion that such plants could engender the equivalent of poison-gas attacks was both surprising and frightening. Similarly, CFCs had proven to be extremely stable, nonreactive chemicals that held none of the threats of a Bhopal-like disaster. The discovery that their use in something as mundane as a deodorant can could nonetheless threaten life on the planet was therefore surprising in the extreme.

THE PICTURE CUBE, INC.—PHIL SAVOIE

Deer ticks, such as this one perched on a matchstick, are the main carriers of Lyme disease, one of several serious diseases to emerge in recent decades.

Few surprises, however, are surprises to everyone. In almost every case, someone has had a premonition of the surprise, if only in general terms. This characteristic of surprise makes for a rich scientific endeavor in risk assessment as well as for headlines in the newspapers. As it happens, important books warning of the general potential for catastrophe appeared in the same years in which the outbreak of Legionnaire's disease and the accident at Bhopal occurred.

In 1976, historian William McNeill, reviewing the role of plagues in human history, noted that

> *it now requires an act of imagination to understand what infectious disease formerly meant to humankind, or even to our grandfathers. Yet it is to be expected when human beings learn new ways of tampering with complex ecological relationships, the control over microparasites that medical research has achieved since the 1880s has also created a number of unexpected byproducts and new crises.*[9]

He goes on to cite "the new diseases of cleanliness," the "mutations of other infectious organisms," the possibility "that some hitherto obscure parasitic organism may escape its accustomed ecological niche," and biological warfare as possible sources of new plagues.[10] The first three have since come to haunt us and questions as to the products of biological warfare persist.

Similarly, in 1984, sociologist of technologies Charles Perrow wrote a book on "normal accidents," arguing that complex and tightly coupled systems of people and technology create accidents waiting to happen. His chapter on petrochemical plants identified the ingredients of the Bhopal disaster and anticipated vapor-cloud explosions.[11] He erred only in not anticipating that Bhopal's vapor cloud would be so poisonous and that normal accidents in crowded developing countries carry increased potential for death.

It is also clear that all the pieces of the CFC puzzle were in place before Molina and Rowland put them together. By 1973, inventor and biologist James Lovelock had measured unexpectedly large concentrations of CFCs in the atmosphere, leading many to ponder the implications of their extreme persistence and ubiquity.[12] And scientists studying the possible impacts on the stratosphere of nuclear explosions, supersonic transports, and space shuttles had pointed out that a variety of chemicals—including chlorine—could lead to ozone destruction, increasing ultraviolet exposure and the risk of skin cancer. But no one could imagine how enough chlorine could get into the stratosphere to make a difference.[13] Molina and Rowland's hypothesis (that chlorine originating in ground-level use of CFCs could indeed cause substantial stratospheric ozone depletion) received rapid and widespread attention from the scientific community precisely because the surprise was relatively unsurprising, stemming from several previously accepted but unconnected pieces of information.

All three of the surprises under consideration—Legionnaire's disease, the Bhopal disaster, and the depletion of the ozone layer—were negative. Although many environmental surprises are indeed negative,[14] it is important to note that people tend to pay more attention to unanticipated events when the consequences are harmful. As it happens, there have also been a number of positive environmental surprises that would temper our gloomy expectations of environmental degradation and human suffering if we would only

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recognize them. For example, the biomass of temperate forests has been increasing in recent years despite—and possibly because of—the effects of acid rain and other pollutants.[15] Yet, while the negative effects of acid rain on particular places or species of trees have been widely disseminated and are common knowledge, this positive development is little known outside of professional circles.[16]

Finally, each of the three surprises opened windows of opportunity for society to increase its capacity to manage environmental problems. Although in some cases these opportunities have been frittered away, in others they have been used to institute lasting and important changes. The surprise appearance of Legionnaire's disease may have been one of the opportunities that was frittered away. While it initiated a flurry of both scientific and technical work to determine the cause of the disease and prevent its transmission, it took the appearance of AIDS and other viruses to change the mindset that infectious disease had been completely conquered.[17]

Such mindsets, of course, are common both in individuals and in institutions and render them largely oblivious to the reality of surprise. Psychologists have long studied the phenomenon of cognitive dissonance, i.e., how people tend to repress information that confounds their expectations. Institutions also tend to repress such information, and they have an additional incentive to do so when the information poses a threat to their goals or their usual ways of doing things or presents new and costly challenges.[18]

The Bhopal disaster, by contrast, led to constructive change. To an unprecedented degree, it focused the attention of Indian regulators, multinational corporations, and international institutions on managing the risks of chemical manufacturing. From this emerged significant reforms to India's legal and regulatory systems, the adoption of strict corporate codes of conduct (such as the internationally adopted Business Charter for Sustainable Development and the Responsible Care program[19]), and the implementation of information systems for chemical hazard management by various U.S. and international organizations. Though these measures do not go as far as many would like, there is little question that they have improved the world's capacity to handle the environmental and health risks of chemical manufacturing. And there is no doubt that we have attained this capacity sooner than we would have without the dreadful surprise of Bhopal.[20]

The surge of concern about risks to the stratospheric ozone layer that arose in the wake of Molina and Rowland's surprising hypothesis also helped to bring about a number of lasting improvements in society's ability to manage related risks. These include the strengthening of a basic research program on atmospheric chemistry, the initiation of work on CFC substitutes by DuPont and other manufacturers, and the emergence of groups committed to CFC policy formulation in both the government and nongovernmental communities. At least as important, recognition of the global character of the problem led to an international consultative process that slowly but inexorably laid the groundwork for the Vienna Convention and its subsequent protocols.[21] Many of the new institutional arrangements operated almost invisibly during the late 1970s and early 1980s as the

(continued on page 28)

VISUALS UNLIMITED—L. KIFF

Originally hailed as an important pesticide, DDT was later implicated in the fatal thinning of the eggshells of birds such as this brown pelican.

Environmental Surprise
(continued from page 11)

stratospheric ozone issue subsided into relative obscurity. But when the second surprise of the Antarctic ozone hole arrived in 1985, it was the foundation of science and technology, domestic policy, and international treaties put in place during the first ozone crisis that enabled the world to respond rapidly and effectively.

Types of Environmental Surprises

To improve society's ability to anticipate and respond to the environmental surprises of the next 25 years, it would be useful to have some systematic ways of thinking about and classifying environmental surprises. Several attempts have already been made in this area.[22] In 1986, physicist and science policy scholar Harvey Brooks sketched a "typology of surprises" arising from the interactions of technology, institutions, and development that identified three general types of surprise: discrete events that are not expected, such as the oil shock of 1973, industrial accidents, political coups, and major natural catastrophes; discontinuities in long-term trends, including the acceleration of U.S. oil imports after 1966, stagflation in Organisation for Economic Cooperation and Development (OECD) countries in the 1970s, and the increase in energy efficiency in the same countries after 1973; and sudden public awareness of new information, such as the relationship between CFC production and stratospheric ozone depletion, the hazards of recombinant DNA techniques, and asbestos-related cancer in industrial workers.[23]

It would be useful to have some systematic ways of thinking about and classifying environmental surprises.

Along the same lines, conservation scientist Norman Myers has suggested that research focus on two categories of environmental surprises: discontinuities, where a little more or a little less of something can create a distinctively new situation; and synergies, where two or more environmental processes interact so that the net result is more than the sum of the individual effects. As examples of discontinuities, he cites global warming, land shortages, and the use of fuelwood in developing countries. As examples of synergies, he cites the potential interactions between global warming and ozone depletion and between global warming and endemic plant disease.[24]

Taking a somewhat different tack, a recent interdisciplinary workshop on surprise and global change focused on the nature of the ignorance that leads to surprise. This workshop concluded that there are two basic types of ignorance: that which is easy to reduce (through either personal or collective learning) and that which is hard to reduce (because it reflects the particular ways in which people view the world or the limitations of current knowledge itself).[25]

The approach taken in this article, however, is based on a distinction in risk assessment that is useful for ordering the different ways of anticipating and responding to surprise. In trying to understand potential threats, risk assessors typically distinguish between *events* (things that happen),

PANOS PICTURES—ANDERS GUNNARTZ

Lenin's statue stands guard over the town of Naroditje, Ukraine, evacuated after a nuclear accident at nearby Chernobyl.

their harmful *consequences* (people are hurt, ecosystems are damaged, or property is destroyed), and the *causal connections* between them (a particular event results in a particular type of harm). Such distinctions are important because the chance that something will go wrong may be more or less independent of the harm it will cause. For instance, the harm done by an exploding storage tank will depend more on the number of people in the vicinity and the nature of the remedies available to them than on the probability of an explosion per se. Moreover, if our causal models are wrong, we may mistake the relationships between particular events and consequences, thus expending time, effort, and money addressing the wrong problem.

The examples of environmental surprise given above thus reflect two broad types of expectations regarding the connections between events and their consequences. In the first, surprise arises from unanticipated events, in the second from unanticipated or wrongly attributed consequences.

Unanticipated Events

In both the Bhopal and Legionnaire's disease cases, the big surprise lay not in the causal connections between events and consequences but in the occurence of the events at those particular times and places. Although (in a very general way) we expect such events to occur, the probability of any particular occurrence is so low that it always surprises us. Bhopal, in fact, exemplifies a major focus of risk assessors: rare events with very large but predictable consequences. As shown in Figure 1 on this page, a number of similar environmental surprises have occurred over the last 25 years, including chemical releases at Seveso, Italy, nuclear releases at Three Mile Island and Chernobyl, and the eruption of Mount St. Helens in Washington State.[26]

Similarly, disease-causing bacteria are ever-present, and we try to prevent their spread in ways ranging from covering our mouths when we cough to implementing elaborate public health measures. But when *Legionella* got into an air conditioning system at a convention, it caused so many cases of illness and death that it shocked us. The surprise was not that such organisms could cause harm, but that they did so under circumstances where we thought we had them under control. Similar surprises over the last 25 years include other diseases such as Hanta virus and Lyme disease, radon in homes, and zebra mussel contamination in the Great Lakes.

Unanticipated Consequences

In the ozone depletion case, the surprise was in a sense greater than with Bhopal and Legionnaire's disease. Here it was our expectations about causation itself that failed: We believed we knew the risks CFCs posed, and destruction of the ozone layer was not among them. CFCs were thus dispersed throughout the world long before we understood the harm that they could cause. A number of similar substances have surprised us over the last 25 years, including asbestos fibers, non-point source groundwater pollutants, DDT, lead in paint and gasoline, and secondary cigarette smoke.

The CFC story also illuminates another type of causal surprise, i.e., where the consequences are the focus of attention but are attributed to the wrong cause. At the time Molina and Rowland pointed out the significance

Figure 1. Types of surprise and societal responses.

	Surprising Events		Surprising Consequences/Causation	
Description	Rare events with serious consequences	Common events that elude detection/prevention	Unexpected consequences	Expected but mistakenly attributed consequences
Examples	Bhopal Seveso, Italy Three Mile Island Chernobyl Mount St. Helens	Legionnaire's disease Hanta virus Lyme disease Radon gas in homes Zebra mussels in the Great Lakes	CFCs Lead in paint and gasoline Asbestos fibers Secondary cigarette smoke Groundwater pollution	Stratospheric ozone depletion Ground-level ozone damage Forest damage
Generic social responses	Hazard identification, event prevention, consequence reduction			
Specific social responses	Emergency response to reduce consequences	Screening and monitoring for earlier detection	Modes of analysis to consider the unthinkable	Modes of analysis that emphasize multiple and unknown causation

of CFCs, for instance, other research (mainly on supersonic transports, space shuttles, and nuclear explosions) had led scientists to believe that water vapor and nitrogen oxides were the major threats to the ozone layer. Although a few scientists had shown that chlorine could cause problems, no one believed enough of it could get into the stratosphere to do so. The surprise was thus not that ozone depletion could occur, but that the major cause might be ordinary spray cans used at ground level rather than advanced technologies operating in the upper atmosphere.

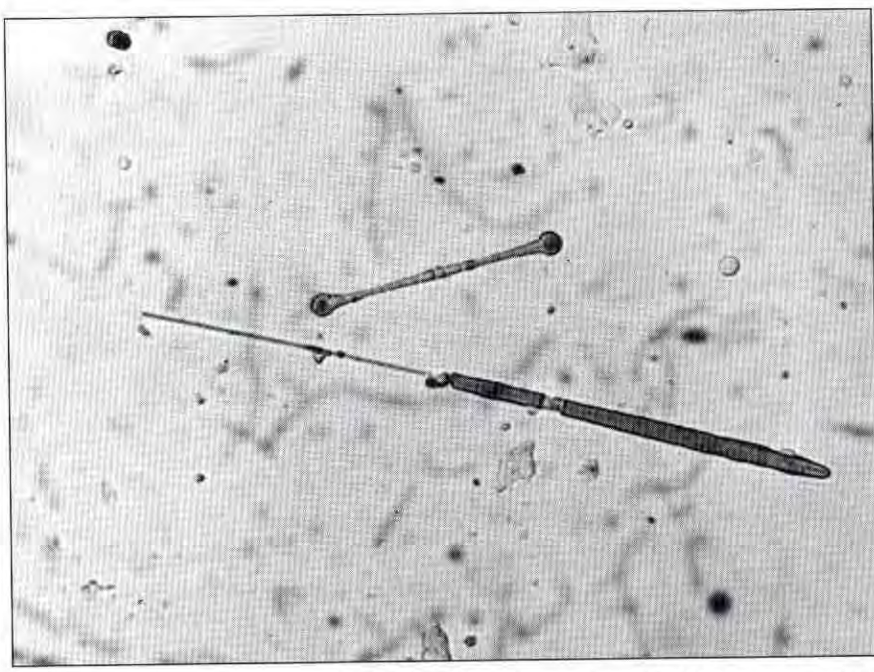
Coping with Surprise

In the examples of environmental surprise given so far, there is a definite pattern of societal response, an evolution in the ways of anticipating and coping with surprise. To some extent, of course, coping with unexpected hazards is little different from coping with expected ones. The hazards need to be identified and a causal connection between unwanted consequences and precipitating causes or events established. Then, to the extent possible, the events that make the threats a reality have to be prevented from occurring and any unavoidable consequences mitigated.

Well-defined methods of risk assessment and management exist for each of these tasks. Hazards can be identified by appropriate research, using the techniques of engineering analysis, screening, monitoring, and diagnosis. Events can be prevented by limiting the use of hazardous materials, strengthening the inherent safety of devices, and improving human oversight. Consequences can be reduced by limiting exposure to hazards, reducing the vulnerability of humans and ecosystems to such hazards, and providing quick and appropriate treatment when such exposure occurs.

But surprise also changes the pattern of coping. In one sense, surprise arises precisely from the failure of the current system to identify, prevent, and reduce hazardous threats, events, and consequences. Paradoxically, the very success of that system can also fuel surprise, whether through complacency born of our substantial managerial skill or through the sorts of complex system responses described in the box on page 8. Moreover, the inevitable failures are thrown into contrast—and thus become surprises—by the general tendency toward success. Neither Legionnaire's disease nor the Bhopal incident would have surprised people living in the 19th century, when epidemics were common and steam boilers frequently exploded.

Part of the solution to unexpected events is simply to monitor hazards not only where they are supposed to be but also where they are not.



VISUALS UNLIMITED—GEORGE MUSIL

Asbestos fibers, shown here in a human lung, have been responsible for numerous cases of respiratory disease.

Despite the inevitability of surprise, societies can better cope with it and, indeed, use it creatively. Better coping entails both addressing particular surprises and strengthening generic social structures and institutions. As shown in Figure 1 on page 29, there are specific types of response appropriate to the two general types of surprise described in the previous section.

In the case of unexpected events (where it is expectations regarding the timing or location, but not the causation, of hazards that are violated), standby capacity for quick and effective action to reduce the consequences is generally needed. And clearly, for surprises such as Legionnaire's disease, which involve the unexpected appearance of a (generally) known problem, measures to provide earlier detection would be particularly helpful.

The capacity to cope with this type of surprise has generally improved over the last 25 years, largely in response to the surprises that we have experienced. Standby capacity is now in place (at least in the wealthier countries) for many environmental problems, including such disasters as oil spills, releases of toxic materials, nuclear accidents, earthquakes, and floods, as well as diseases. In addition, generic responses (in the form of emergency and disaster management capability) have improved considerably.

Part of the solution to unexpected events is simply to monitor hazards not only where they are supposed to be but also where they are not. The key often lies in the way data that are at odds with expectations (so-called "outliers") are handled. A classic example is the seasonal hole in the ozone layer over Antarctica, which was almost missed because expectations tended to override actual observations. The theory developed in the wake of Molina and Rowland's paper predicted that the largest ozone depletion would occur in tropical latitudes. Polar regions were of interest primarily as relatively clean background sites. Thus, U.S. satellite measurements that indicated seasonal depletions over Antarctica were treated as suspect. Comparisons with ground-based data from the United States' South Pole station, which showed no depletion, only confirmed these initial suspicions. As a result, the satellite data were set aside as unexplained, but relatively uninteresting, anomalies. In fact, however, it was the ground data that were wrong.[27] The hole was finally discovered by a British team under J. C. Farman that decided to believe its own ground-based information even though theory cast doubt on it.[28]

Today there is much greater awareness that anomalies may actually reflect previously undetected phenomena rather than measurement error. For instance, epidemiological monitoring has become more sensitive to the unexpected, especially the appearance of "tropical" diseases in temperate countries.

For the other type of surprise, which involves unexpected consequences from familiar events, the appropriate coping strategies are less obvious. Nonetheless, some progress has been made. In particular, the lessons of DDT and CFCs have been taken to heart: Before the general introduction of new chemicals, extended appraisals systematically explore a wide range of possible movement patterns and interactions. Risk prioritization schemes have also been proposed that flag ubiquitous substances and organisms for special attention, regardless of whether causal connections to unwanted consequences have been established.[29] The systematic search for discontinuities and synergies that Myers proposed aids in this process. Backcasting, the opposite of forecasting, is also useful for increasing sensitivity.[30] Being open to the possibilities of multiple causation can help prevent the rush to judgment that often characterizes errors in attribution.[31] (The box on this page outlines some of the techniques used to anticipate surprises, while that on page 33 illustrates the use of such techniques to envision surprise outcomes for greenhouse gas emissions.)

ANTICIPATING SURPRISES

Even though surprises are not completely predictable, there are a number of techniques one can use to anticipate them—that is, to generate visions of the future in which the improbable comes to pass. One such technique is *surprise theory*, which focuses on the principles underlying unexpected events and developments (see the box on page 8). Another is *historical retrodiction*, which examines empirical cases of surprise to determine whether the seeds of future surprises are apparent to hindsight and, if so, how they can be recognized ahead of time.

Four other techniques relate to the methods of identifying trends and making projections based on them. The first involves introducing *contrary assumptions* into the analysis. For example, in predicting population, analysts usually make several different assumptions about birth and death rates and how they will change over time; these assumptions yield a range of predictions, some of which are more probable than others (the median projection is the one used most frequently). Seldom, however, do the assumptions entail major disruptions such as war, economic depression, plague, or a change in deep-seated values. By including such disruptions in the calculations, analysts can get a better idea of what is likely to happen in extreme cases. A variant of this technique involves *asking experts* what would surprise them, often defining such surprises in probabilistic terms (e.g., as events with only a 1 or 2 percent chance of actually occurring).

Third, one can simulate surprise in *models of system dynamics* that explore how current trends produce surprising results due to their interaction. Finally, there is a technique known as *imaging* in which one imagines an unlikely event (say, a global population much smaller than the one today) and then tries to construct a plausible scenario—a form of backcasting—by which it might be realized.

Some recent studies have used the last four techniques to produce credible scenarios with major elements of surprise. One examined a hypothetical transfer of world leadership from the West to South Asia by 2075 as well as the catastrophe-free absorption of a future population four times the current one.[1] In another, scientists and intellectuals defined a hopeful future for Africa 100 years after Ghanaian independence and asked how it might be achieved.[2] In a third, scientists studying global change created surprising droughts in the Amazon and air pollution in thinly populated places through the interaction of diverse current trends.[3]

1. U. Svedin and B. Aniansson, eds., *Surprising Futures: Notes from an International Workshop on Long-Term World Development* (Stockholm: Swedish Council for Planning and Coordination of Research, 1987).

2. C. Achebe, G. Hyden, C. Magadza, and A. P. Okeyo, eds., *Beyond Hunger in Africa: Conventional Wisdom and an Alternative Vision* (Portsmouth, N.H.: Heinemann, 1990).

3. W. C. Clark, "Visions of the 21st Century: Conventional Wisdom and Other Surprises in the Global Interactions of Population, Technology, and Environment," in K. Newton, T. Schweitzer, and J.-P. Voyer, eds., *Perspective 2000: Proceedings of a Conference Sponsored by the Economic Council of Canada* (Economic Council of Canada, 1988), 7.

Generic institutions and processes can also be strengthened, beginning with efforts to regard surprise not as unusual but as normal and inevitable. The previously mentioned workshop on surprise and global change[32] suggested ways of improving the anticipation of scientific surprises and of increasing human adaptability to them. To improve anticipation, participants proposed encouraging research efforts that synthesize information (i.e., "putting the puzzles together"), that pay particular attention to anomalies and outliers, that operate at the edges of concepts and across disciplines, and that are "skeptically welcoming" of unconventional views. To increase resilience and adaptability, they recommended diversifying economic activities and avoiding technological monocultures; strengthening entitlements to resources as broadly defined, thus providing robust safety nets and better disaster coping systems; and adopting the "adaptive management" approach to the environment, whereby surprises would serve as useful learning experiences for societies.[33]

The Future of Environmental Surprise

The next 25 years will surely bring more surprises. The occurrence of such surprises, of course, will not be new. What will be new is the rapidity with which they emerge, the complexity of their sources and consequences, and the difficulty we will experience in devising appropriate institutional responses. Environmental surprises will arise out of such phenomena as the interconnected global economy; increasing democratization; the movement of peoples, life forms, and products; the newer molecular-level technologies of biology and materials; the transfer of older technologies to new and different settings; and even the technological and behavioral fixes for current environmental problems.[34]

Even more important than the changing nature of surprise may be the shift in our attitudes toward it. It is possible, for instance, that recent advances in environmental science and the widespread availability of information will make us overconfident about our ability to anticipate and manage surprise—and thus, paradoxically, make us more vulnerable to it. On the other hand, as we experience more and more surprise, each subsequent violation of our expectations is likely to be somewhat less disturbing. This is in some ways comforting, because it will allow us to adjust to rapidly changing circumstances and still maintain hope and optimism about the future.

Yet there is a risk in becoming too comfortable. Surprise remains perhaps the most important vehicle for periodically shaking us out of our indifference to environmental degradation and our preoccupation with other tasks. It is through the windows of opportunity created by such events as Legionnaire's disease, Bhopal, and ozone depletion that many of our most important institutions and ideas regarding the environment have been launched.

The poet Paul Valery once stated that Napoleon's decline started when he was no longer astonished.[35] If we as a society lose our capacity to be astonished at the surprises emerging from our interactions with the environment, we will be the poorer for it. For if surprise has often marked the frustration of our plans and the failure of our policies, it has also contributed greatly to both our motiva-

Even more important than the changing nature of surprise may be the shift in our attitudes towards it.

H. ARMSTRONG ROBERTS

The eruption of Mount St. Helens was a rare event but one with predictable consequences.

GREENHOUSE GAS SURPRISES

Exercises conducted at a workshop sponsored by the Aspen Global Change Institute in 1994[1] offer some important insights into the nature of surprise and the ways of envisioning it. Participants were first asked about future surprises linked to global change; their responses were then classified by degree of impact on the concentration of carbon dioxide in the atmosphere over the next century. There was general agreement that this would double and that any other outcome—in either direction—would be surprising. Next they were asked to use the techniques of backcasting and imaging (described in the box on page 31) to envision how lower and higher concentrations might come about. Their responses were as follows:

A lower concentration of carbon dioxide, reflecting a rapid decline in world emissions, could result from such events as

- the implementation of strong intertional agreements
- rapid decarbonization, occurring because low-cost biomass alternatives are developed; artificial photosynthesis becomes possible; safe, inexpensive nuclear power is developed; large natural gas discoveries are made in China; and China and Brazil develop major biomass industries
- sharp declines in energy-GNP ratios because low-energy technology is adopted worldwide and development increases per capita GNP significantly
- sharp declines in world economic growth rates resulting from the demise of nation-states, leading to conflict and collapse and the emergence of a deadly new virus that reduces population
- much less deforestation in tropical areas

A higher than expected concentration of carbon dioxide, reflecting much larger emissions of carbon dioxide and/or the saturation of carbon sinks, might result from

- the failure to adopt the proper policies because there are both winners and losers and no consensus is reached; environmental concerns are given low priority; and the demise of nation-states leads to conflict and collapse
- the cessation of decarbonization because R&D on low-carbon energy sources is discontinued; accidents cause all nuclear plants to be shut down; China continues to use coal as it primary fuel; and India increases its use of coal
- an end to the decline in energy-GNP ratios as a result of fertility decline not occurring in the developing world; energy prices remaining low; energy conservation proving too costly to implement; and the switch to a service economy in the developed world proceeding more slowly
- increased deforestation, occurring because Siberia experiences major deforestation and land degradation and relative poverty in the developing world leads to continuing loss of land cover

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1. "Elements of Change 1994," pt. 2 of *Anticipating Global Change Surprises*, edited by S. J. Hassol and J. Katzenberger (Aspen, Colo.: Aspen Global Change Institute, 1995), 144.

tion and our opportunity to do better. We could well do worse than to wish that the second 25 years of Earth Days will be as surprising as the first.

NOTES

1. W. C. Winn Jr., "Legionnaire's Disease: Historical Perspective," *Clinical Microbiology Reviews* 1, no. 1 (1988): 60.

2. M. Mukerjee, "Persistently Toxic: The Union Carbide Accident in Bhopal Continues to Harm," *Scientific American*, June 1995, 16, 18. See also B. Bowonder, J. X. Kasperson, and R. E. Kasperson, "Avoiding Future Bhopals," *Environment*, September 1985, 6.

3. "Bhopal," in R. A. Eblen and W. R. Eblen, eds., *The Encyclopedia of the Environment* (Boston, Mass.: Houghton Mifflin Company, 1994), 58.

4. Ibid.

5. Mukerjee, note 2 above.

6. S. Cagin and P. Dray, *Between Earth and Sky: How CFCs Changed Our World and Endangered the Ozone Layer* (New York: Pantheon Books, 1993).

7. M. Molina and F. S. Rowland, "Stratospheric Sink for Chlorofluoromethanes: Chlorine Atom-Catalysed Destruction of Ozone," *Nature* 249 (1974): 810. See also M. F. Kowalok, "Common Threads: Research Lessons from Acid Rain, Ozone Depletion, and Global Warming," *Environment*, July/August 1993, 12.

8. See R. E. Benedick, *Ozone Diplomacy: New Directions in Safeguarding the Planet* (Cambridge, Mass.: Harvard University Press, 1991); S. L. Roan, *Ozone Crisis: The 15-Year Evolution of a Sudden Global Emergency* (New York: Wiley and Sons, 1989); K. T. Litfin, *Ozone Discourses: Science and Politics in Global Environmental Cooperation* (New York: Columbia University Press, 1994); and G. Brasseur, "The Endangered Ozone Layer: New Theories on Ozone Depletion," *Environment*, January/February 1987, 6.

9. W. McNeill, *Plagues and Peoples* (Garden City, N.Y.: Anchor Books, 1976), 254 n.

10. Ibid., pages 254–56.

11. C. Perrow, *Normal Accidents: Living with High Risk Technologies* (New York: Basic Books, 1984).

12. J. E. Lovelock, R. J. Maggs, and R. J. Wade, "Halogenated Hydrocarbons In and Over the Atlantic," *Nature* 241 (1973): 194–96.

13. An accessible treatment of the early years of the ozone debate is provided in L. Dotto and H. Schiff, *The Ozone War* (New York: Doubleday, 1978). Early papers dealing with the role of chlorine include P. J. Crutzen, "A Review of Upper Atmospheric Chemistry," *Canadian Journal of Chemistry* 52 (1974): 1568; R. S. Stolarski and R. J. Cicerone, "Stratospheric Chlorine: A Possible Sink for Ozone," *Canadian Journal of Chemistry* 52 (1974): 1610; and S. C. Wofsy and M. B. McElroy, "HO_X, NO_X, and ClO_X: Their Role in Atmospheric Photochemistry," *Canadian Journal of Chemistry* 52 (1974): 1582.

14. See, for example, N. Myers, "Environmental Unknowns," *Science* 269 (21 July 1995): 358, which only notes negative surprises.

15. P. E. Kauppi, K. Mielikainen, and K. Kuusela, "Biomass and Carbon Budget of European Forests, 1971–1990," *Science* 256 (1992): 70.

16. Gregg Easterbrook has strongly challenged what he sees as the prevailing negativism of environmental organizations and public reporting. He argues that environmentalists fail to acknowledge and take credit for the substantial positive improvements in the environment that have followed from their initial activities. See G. Easterbrook, *A Moment on the Earth: The Coming Age of Environmental Optimism* (New York: Viking Press, 1995).

17. Winn, note 1 above; and Philip Landrigan, Mt. Sinai School of Medicine, New York, and Washington Winn, University of Vermont College of Medicine, Burlington, personal communications with the authors, November 1995.

18. See E. A. Parson and W. C. Clark, "Sustainable Development as Social Learning: Theoretical Perspectives and Practical Challenges for the Design of a Research Program," in L. H. Gunderson, C. S. Holling, and S. S. Light, eds., *Barriers and Bridges to the Renewal of Ecosystems and Institutions* (New York: Columbia University Press, 1995), 428.

19. See J. Nash and J. Ehrenfeld, "Code Green: Business Adopts Voluntary Environmental Standards," *Environment*, January/February 1996, 16.

20. An excellent retrospective on the legacy of Bhopal is provided in S. Jasanoff, ed., *Learning from Disaster: Risk Management after Bhopal* (Philadelphia, Pa.: University of Pennsylvania Press, 1994). See also M. Mukerjee, "Toxins Abounding: Despite the Lessons of Bhopal, Chemical Accidents Are on the Rise," *Scientific American*, July 1995, 22.

21. For a detailed discussion, see E. A. Parson and O. Greene, "The Complex Chemistry of the International Ozone Agreements," *Environment*, March 1995, 16.

22. See R. W. Kates, "Success, Strain, and Surprise," *Issues in Science and Technology* 2, no. 1 (1985): 46; U. Svedin and B. Aniansson, eds., *Surprising Futures: Notes from an International Workshop on Long-Term World Development* (Stockholm: Swedish Council for Planning and Coordination of Research, 1987); C. Achebe, G. Hyden, C. Magadza, and A. P. Okeyo, eds.,