Probabilities Behaving Badly: Complexity Theory and Environmental Uncertainty

Daniel A. Farber[*]

TABLE OF CONTENTS

[*] Sho Sato Professor of Law, University of California at Berkeley. Thanks to Jim Chen Brett McDonnell, and Christopher Stone for helpful comments.

Order is indeed the dream of man, but chaos, which is only another word for dumb, blind, witless chance, is still the law of nature.[1]

INTRODUCTION

Notwithstanding our best efforts at prediction, from time to time the world presents us with nasty surprises.[2] Engineers explore highly unlikely worst case scenarios and discard them as too far-fetched to worry about, only to learn, after the space shuttle is destroyed, that some of their concerns were close to what happened.[3] A leading regulatory economist meticulously analyzes the costs and benefits of increased airport security, concluding that the minor risks presented by terrorism do not justify heightened security, only to learn one morning that terrorists have killed three thousand people.[4] Events of this kind present a dilemma to policymakers. It would be paranoid to assume that the worst will always happen. Yet, perhaps paradoxically, it is reasonably foreseeable that non-reasonably foreseeable events will occur from time to time. A planning process that ignores this reality will work satisfactorily nearly all of the time but when failures occur they may be catastrophic. The overwhelming majority of the Lincoln family's theater outings went smoothly, but Mrs. Lincoln doubtless took little comfort from this observation.

Environmental regulation has grappled with this problem for several decades. This essay assesses these efforts in light of the developing theory of dynamic systems, sometimes called complexity theory or chaos theory. I will explore the implications of one lesson of complexity theory, which involves the peculiar statistical behavior of complex systems. Even people who have never heard of a bell curve ("normal distribution") have an intuitive sense of its properties, with most events bunched near the average and extreme outcomes fading away quickly. If the average cat weights ten pounds, we can expect that most cats will be within a few pounds of the average and we can safely disregard the possibility of a two hundred pound tabby. Complex systems, however, are often characterized by a different kind of statistical distribution

[1] WALLACE STEGNER, CROSSING TO SAFETY 191 (2002). As we will see, the current view is that Stegner was right about "chaos" but wrong to equate it with "chance."

[2] I've taken this phrase from Jeff Howard, *Environmental "Nasty Surprise" as a Window on Precautionary Thinking*, IEE TECH. & SOC'Y MAG., Winter 2002-2003, at 19.

[3] Matthew L. Wald & William J. Broad, *Shuttle Engineers Debated Chances of Grave Damage*, N.Y. TIMES, Feb. 27, 2003 at A1.

[4] *See* Thomas O. McGarity, *Professor Sunstein's Fuzzy Math*, 90 GEO. L.J. 2341, 2364 (2002) (recounting incident involving leading regulatory economist).

called a "power law."[5] If feline weight were subject to a power law, we would find that the vast majority of cats were tiny or even microscopic but that one-thousand-pound house cats would cross our paths now and then. Under a power law, the possibility of freak outcomes, a one ton Siamese, weighs heavily in the analysis, often more heavily than the far more numerous "routine" outcomes, the tiny micro-cats. Indeed, a power law probability distribution makes it somewhat misleading to even talk about "typical" outcomes.

Part I of this essay begins with a reminder of the extent of our uncertainty about environmental problems. It then describes complexity theory and power laws in more detail and reviews preliminary evidence that power laws govern some environmental impacts.

Part II discusses three existing approaches to environmental uncertainty: risk assessment, worst-case analysis, and the precautionary principle. Part II also shows how statistical power laws may be able to provide insight into policy alternatives.

This essay is a tentative exploration of the implications of statistical power laws for environmental policy. To keep this exploration manageable, I will limit myself to a subset of environmental problems that have three characteristics. The first is that the environmental harms in question can be approximated through a large range by a power law. We do not know how many environmental problems fit this description but there is reason to think that at least some do. The second characteristic is that the other side of the regulatory equation — the cost of regulation — is *not* subject to a power law but is instead well-behaved statistically. Chaos theory may apply to some economic issues or technological changes, but for present purposes I put these complications aside.[6] The third shared characteristic of these environmental problems is that we cannot effectively steer our social systems as problems develop so as to forestall potential extreme outcomes before they reach fruition.

Complexity theory provides strong arguments for adaptive management, which involves careful monitoring of systems and

---

[5] For an introduction to power laws, see MANFRED SCHROEDER, FRACTALS, CHAOS, POWER LAWS: MINUTES FROM AN INFINITE PARADISE 103-19 (1991).

[6] For a discussion of economic applications, see J. Barkley Rosser, Jr., *On the Complexities of Complex Economic Dynamics*, 13 J. ECON. PERSP. 169 (Fall 1999). Thus, the fact that complexity theory and power laws are not universal is both a strength and a weakness. The weakness is more obvious: we will need to establish in any particular situation whether this approach applies, and we cannot be sure in advance how many such situations exist. But it is also a strength because it means that the other side of the regulatory equation may be more predictable than the benefits of regulation.

repeated interventions as they evolve.[7] Adaptive management can prevent the worst consequences of a power law from being realized. For present purposes, I also put this consideration aside. This essay does not claim to address all environmental problems. The point is that there may be a significant subclass of problems where power laws change the policy analysis in important ways.

Given these qualifications, and my deliberately tentative analysis, some readers may prefer to view this essay as being in the nature of a thought experiment. In a world where statistical power laws apply to environmental issues, what should environmental policy look like? Perhaps this seems too speculative. It is surely no more speculative, however, than all the law review articles published annually about what legal rules would be appropriate in a world of perfectly rational actors.

I. THE DIMENSIONS OF ENVIRONMENTAL UNCERTAINTY

This essay is not the first, nor will it be the last, to grapple with the proper handling of uncertainty in environmental law. Nor is it unique to note the connection between complexity theory and environmental law. This section will briefly discuss the sources and extent of environmental uncertainty and will then examine complexity theory and the application of power laws to complex systems.

A. The Problem of Uncertainty in Environmental Law

In a book published ten years ago, Chris Stone cogently described the high level of scientific uncertainty surrounding environmental problems, noting that we are only beginning to learn how the world works and that our ignorance extends to global climate, habitat, and biodiversity.[8] Stone made a particular effort to investigate the state of scientific knowledge regarding global climate change.[9] What he and his research assistant found was that "[t]he deeper into the better authorities we fished, the more vague and qualified the projections we found."[10]

---

[7] Adaptive management has received increasing attention from legal scholars. For a good overview, see Bradley C. Karkkainen, *Adaptive Ecosystem Management and Regulatory Penalty Defaults: Toward A Bounded Pragmatism*, 87 MINN. L. REV. 939 (2003). Even if some economic processes are chaotic, they may be more amenable to adaptive management than (for instance) global ecological changes.

[8] CHRISTOPHER STONE, THE GNAT IS OLDER THAN MAN: GLOBAL ENVIRONMENT AND HUMAN AGENDA 24 (1993).

[9] *Id.* at 13-16, 20-23.

[10] *Id.* at xvi-xvii.

Stone's observations remain generally valid today. Consider the two topics he mentioned, biodiversity and climate change. We are still unsure of the number of species in peril. For example, although the most commonly cited figure for the fraction of the global flora threatened with extinction is 13%, another recent estimate is that "as many as half of the world's plant species may qualify as threatened with extinction."[11] Similarly, despite much scientific progress, predictions regarding global climate change are still shrouded in uncertainty.[12] Because of this uncertainty, the International Panel on Climate Change (IPCC) decided to exclude certain probability estimates from its Third Assessment Report (TAR).

> It was the unanimous view of the TAR lead authors that no method of assigning probabilities to a 100-year-climate forecast is sufficiently widely accepted and documented . . . to pass the extensive IPCC review process. Three reasons stand out: the difficulty of assigning reliable probabilities to socioeconomic trends (and hence emissions) in the latter half of the 21st century, the difficulty of obtaining consensus ranges for quantities like climate sensitivity, and the possibility of a nonlinear response in the carbon cycle or ocean circulation to very high late-21st-century greenhouse gas concentrations.[13]

In a more recent discussion of one impact of global climate change, the same author concluded that a "satisfactory understanding of . . . variability of Arctic climate remains elusive" and that current models fit the data poorly and "tend to produce a tremendous spread in their predicted future warming in the Arctic."[14]

The problem is not simply that we are in the early stages of scientific investigation but also that many environmental issues involve complex dynamic systems with nonlinear properties. Instead of the familiar "balance of nature," ecologists currently tend to view the biosphere as characterized by complicated, chaotic interactions in which any equilibrium is purely temporary.[15] The current view stresses the highly

---

[11] Nigel Pitman & Peter Jergenen, *Estimating the Size of the World's Threatened Flora*, 298 SCI. 989 (2002).

[12] John Reilly et al., *Uncertainty and Climate Change Assessments*, 293 SCI. 430, 430 (2001).

[13] Myles Allen et al., *Uncertainty in the IPCC's Third Assessment Report*, 293 SCI. 430 (2001).

[14] Reilly, *supra* note 12 at 430.. One difficulty is that drastic climate changes may occur relatively quickly. *See* R.B. Alley, *Abrupt Climate Change*, 299 SCI. 2005 (2003).

[15] For an excellent summary of the recent literature, see Fred Bosselman, *What Lawmakers Can Learn from Large-Scale Ecology*, 17 J. LAND USE & ENVTL. L. 207, 225 (2002).

stochastic nature of ecosystems.[16] Even when we have successfully diagnosed a problem, uncertainties attend any attempted remedy. For instance, as Jim Chen explains:

> Overfishing has destroyed the commercial viability of at least half of the world's fish stocks. In the United States, some 45 percent of fish stocks are overfished; the populations of some species have fallen below 10 percent of optimum levels. Our inability to ascertain safe harvest levels for even intensely studied fish stocks undermines our confidence in the evidently illusory notion of "sustainable" fishing.[17]

Likewise, J.B. Ruhl points to several sources of uncertainty, including the poorly understood connections between species within an ecosystem, the extent of habitat needed to support a long-term viable population (especially for large carnivores), the effects of invasive species, and the potential negative effects of conservation efforts.[18] Because there are large numbers of interconnections between species, calculating all of the effects of adding or removing species can be impossible.

> For instance, adding predators of a given species into an ecosystem should surely have a negative effect on that predator's prey populations. But extensive calculations made by Peter Yodzis, among others, on real food webs show that in many cases adding predators can increase the number of prey. Indirect pathways very frequently dominate direct pathways in determining the long-term outcomes of perturbations. . . . Peter de Ruiter and coworkers have shown that small links can have a large impact on stability, whereas interactions involving an important flow of energy can be almost irrelevant to stability.[19]

Some of the implications for environmental regulation are surveyed in J.B. Ruhl, *Thinking of Environmental Law as a Complex Adaptive System: How to Clean Up the Environment by Making a Mess of Environmental Law*, 34 HOUS. L. REV. 933 (1997). Recent research on large-scale networks also reveals the emergence of unexpected properties that may make control difficult. *See* Ian Foster, *Unexpected Consequences of Connections*, 297 SCI. 1124 (2002). For an accessible introduction to the subject, including a discussion of implications for ecology, see MARK BUCHANAN, NEXUS: SMALL WORLDS AND THE GROUNDBREAKING SCIENCE OF NETWORKS 138-55 (2002).

[16] *See* Karkkainen, *supra* note 7, at 943.

[17] Jim Chen, *Globalization and Its Losers*, 9 MINN. J. GLOBAL TRADE 157, 189 (2000) (citations omitted). For a more recent discussion of the problem, see Daniel Pauly & Reg Watson, *Counting the Last Fish*, SCI. AM., July 2003, at 44.

[18] Ruhl, *supra* note 15, at 956.

[19] RICHARD SOLE & BRIAN GOODWIN, SIGNS OF LIFE: HOW COMPLEXITY PERVADES BIOLOGY 209 (2000).

Consider in this regard the Canadian government's effort to rescue its failing cod fishery by killing harp seals.[20] The government's reasoning was simple: harps seals eat cod; ergo, fewer harp seals means more cod. The Canadian government insisted that this was a matter of common sense.[21] But this common sense logic overlooks the fact that harp seals eat many other species, which in turn affect even more species. Consequently, the effect of eliminating half a million harp seals per year is hard to predict.

In the face of this overwhelming complexity, it is clearly not possible to foresee the ultimate effect of killing seals on the numbers of some commercial fish. With fewer seals off the Canadian coast, the number of halibut and sculpin might grow, and since they both eat cod, there may well end up being *fewer* cod than before.[22] Moreover, computer simulations show that, while removing some species may have little effect on the overall food web, removing others can cause drastic changes affecting many species.[23]

Uncertainty sometimes becomes a source of panic but can equally become an excuse for ignoring a looming problem. For example, in rejecting the Kyoto Protocol, President Bush emphasized that "no one can say with any certainty what constitutes a dangerous level of warming, and therefore what level must be avoided."[24] As this statement indicates, uncertainty provides political actors with an inviting pretext for inaction.[25] While Bush's assertion was literally true, it also carried the inaccurate implication that we can safely ignore the potential consequences of global warming.[26] In reality, useful benchmarks can be identified, such as the melting of the West Antarctic Ice Sheet or the disruption of large-scale oceanic circulation. We also have some basis for estimating the relevant temperature ranges.[27] Failure to stabilize emissions now does not make catastrophe inevitable but may seriously limit our future options as new information becomes available.[28] It is

---

[20] *See* BUCHANAN, *supra* note 15, at 140.

[21] *See id.* at 140-41.

[22] *Id.* at 141

[23] *Id.* at 152-54.

[24] Brian C. O'Neill & Michael Oppenheimer, *Dangerous Climate Impacts and the Kyoto Protocol*, 296 SCI. 1971, 1991 (2002) (quoting President George W. Bush, Jan. 11, 2001).

[25] *See id.*

[26] *See id.*

[27] *See id.* at 1971-72.

[28] *Id.* at 1972. According to O'Neill and Oppenheimer, "Stabilizing [carbon dioxide] concentrations near 450 ppm would likely preserve the option of avoiding shutdown of the [oceanic circulation system] and may also forestall the disintegration of the [West Antarctic

easier to close our eyes and hope that the problem will go away than to invest substantial resources without a guaranteed payoff.

In the past, we have successfully dealt with similar uncertainties by waiting until the scientific evidence was clear or until a visible disastrous event took place that compelled us to act.[29] Jim Krier has pointed out that this strategy, which he calls "exfoliation," has worked adequately with some environmental problems, such as urban smog, but is less effective with other problems.[30] We simply may not have the luxury of waiting for such clarity to emerge with problems such as global warming or biodiversity loss.

B. *Power Laws and Complex Systems*

Ecological thought has moved away from the idea of equilibrium toward a more dynamic vision. As Bosselman and Tarlock explain:

> [E]cology is following physics as it owes much to chaos theory. Non-equilibrium ecology rejects the vision of a balance of nature. Change and instability are the new constants. . . . Ecosystems are patches or collections of conditions that exist for finite periods of time. The accelerating interaction between humans and the natural environment makes it impossible to return to an ideal state of nature. At best, ecosystems can be managed rather than restored or preserved, and management will consist of series of calculated risky experiments.[31]

Similarly, J.B. Ruhl observes that the "emergence in environmental biology of the concept of ecosystems as unpredictable, dynamically changing systems has injected a heightened awareness of the role of indeterminacy and randomness into evolutionary theory."[32]

To better understand ecosystems, biologists have turned to complexity theory, the mathematical study of nonlinear dynamic systems. Such systems have a number of distinctive qualities. Even if a system is completely deterministic, in the sense that we know the precise

---

ice sheet], although it appears to be inadequate for preventing severe damage to at least one unique ecosystem [coral reefs]. Taking into account uncertainties in the working of the carbon cycle, the cumulative Kyoto target is consistent with this goal. Delaying reductions by industrial countries beyond 2010 risks foreclosing the 450 ppm option." *Id* at 1972.

[29] *See* James E. Krier, *The End of the World News*, 27 LOY. L.A. L. REV. 851, 852-55 (1994) (discussing pattern of air pollution in Southern California).

[30] *Id.* at 855, 858-60.

[31] Fred Bosselman & A. Dan Tarlock, *The Influence of Ecological Science on American Law: An Introduction*, 69 CHI.-KENT L. REV. 847, 869-70 (1994).

[32] Ruhl, *supra* note 15, at 955.

equations that govern its activities, outcomes may be impossible to predict over any extended time period. This attribute is known as "chaos" and involves extreme sensitivity to initial conditions, so that immeasurable variations in the current state of affairs can lead over time to arbitrarily large divergences in eventual outcomes.[33] Such systems also produce a characteristic distribution of outcomes: "a high frequency of small fluctuations, punctuated by the occasional large shift in system conditions."[34]

For present purposes, this unusual statistical distribution is the most significant feature of complexity. Rather than following the familiar bell-curve distribution, complex systems often follow power law distributions. Thus, the frequency of an event is given by its magnitude taken to a fixed negative exponent.[35] A classic example is earthquakes. There are many more small earthquakes than large ones, and the pattern of decay in frequency fits a power law distribution.[36] Other examples include the size of extinction events, the number of species present in a habitat, and the size of the n^{th} smallest species (meaning that almost all species are rare but a few have very large populations).[37]

Some additional explanation of power laws may be helpful for the non-mathematically inclined. Albert-Laszlo Barabasi, a physicist who studies complex networks, explains why power laws are important. Contrasting power laws with the normal curve governing characteristics such as human heights, he points out:

> Power laws are very different from the bell curves describing our heights. First, a power law distribution does not have a peak. Rather, a histogram [frequency distribution] following a power law is a continuously decreasing curve, implying that many small events coexist with a few large events. If the heights of an imaginary planet's inhabitants followed a power law distribution, most creatures would be really short. But nobody would be surprised to see occasionally a hundred-foot-tall monster walking down the street. In fact, among six billion inhabitants there would be at least one over 8,000 feet tall. So the distinguishing feature of a power law is not only that there are many small events but that the numerous

---

[33] *Id.* at 947.

[34] *Id.* at 952.

[35] *See* SOLE & GOODWIN, *supra* note 19, at 201.

[36] SIMON LEVIN, FRAGILE DOMINION: COMPLEXITY AND THE COMMONS (1999).

[37] *See* SOLE & GOODWIN, *supra* note 19, at 201. A similar distribution obtains for gaps in rainforests. *Id.* at 205. For another example of power laws in ecology, see LEVIN, *supra* note 36, at 55.

tiny events coexist with a few very large ones.[38]

Such outliers are much less likely when a normal distribution is involved. In more technical terms, "[b]ell curves have an exponentially decaying tail, which is a much faster decrease than that displayed by a power law."[39]

One consequence is that events with power laws are scale-free; there is no characteristic size that is typical of the system.[40] What power laws challenge us to do then is give up the view of the world as consisting of typical events with infrequent random variations. Instead, we must accept that there is no "average" event. There are simply many small ones, a few larger ones, and occasionally extremely large ones.

Another paradoxical aspect of power laws is that additional information can have startling effects on probability estimates. Suppose, for example, that the amount of time to complete a given task is given by a power law, with an average time of three days. If we know that a job has already taken five days, we might expect it to be done in another three days and probably less. But in fact, the expected time to completion is now fifteen days![41] The reason is that the curve flattens out much less quickly as we move farther out. As the job has already taken five days, we have moved beyond the part of the curve where completion time declines rapidly and moved into a zone where probabilities drop off much more slowly.

It is particularly intriguing that power laws seem characteristic of complicated networks. Some examples include the World Wide Web, where the number of links to a particular site follows a power law, as do the number of citations to a given physics paper, and even the number of other actors with whom a given Hollywood star has appeared.[42] On the Web, for example, about 90% of all pages are the targets of ten or fewer links, while about three out of a sample of two hundred million had roughly a million other pages pointing to them.[43] As it turns out, Supreme Court opinions also appear to follow a power law in terms of their frequency of citation.[44] This seems to be a widespread phenomenon that is not tied to the specific dynamics of a given network or system.

---

[38] ALBERT-LASZLO BARABASI, LINKED: THE NEW SCIENCE OF NETWORKS 67-68 (2002).

[39] *Id.* at 68 n.1.

[40] *Id.* at 70.

[41] This example is given in SCHROEDER, *supra* note 5, at 157.

[42] BARABASI, *supra* note 38, at 67-69.

[43] *Id.* at 58.

[44] *See* Daniel A. Farber, *Earthquakes and Tremors in Statutory Interpretation, in* ISSUES IN LEGAL SCHOLARSHIP, *at* http://www.bepress.com/iss3/art11 (last visited Sept. 19, 2003).

Scale-free systems and their accompanying power laws can have disconcerting properties. For example, it is possible for a variable subject to a power law to have an infinite variance or even an infinite expected value.[45] The expected value is the probability of an event times its value. Variance is a measure of uncertainty. The chances of a large event may decrease rapidly but not rapidly enough to make up for the increasing magnitude of the event. (For example, consider x varying from one to infinity, with $p(x) = x^{-2}$.) If we are talking about an uncertain environmental harm, this means that either the expected value of the harm might be infinite, or the expected value might be finite but the variance might be infinite.

How seriously should we take these models? The actual infinities may be discounted because the scale-free property is unlikely to hold over the entire range of a phenomenon; for example, there is an absolute limit to the possible amount of an environmental harm (complete destruction of the biosphere). At best, scale-free models and their accompanying power laws are only approximations of reality. The work being done by students of complexity theory is impressive and has some intriguing empirical support. But it could turn out to be a flash in the pan. And it would not be the first time in science that a lovely theoretical insight has failed to work out. It is a little early to proclaim complexity theory the definitive new scientific revelation.

For present purposes, we can take a more modest lesson. Rather than viewing complexity theory and power laws as an absolutely accurate description of reality, we can at least draw an important insight. There are good reasons to suspect that some important characteristics of real systems have what a statistician would call very "fat tails," making extreme events *much* more likely than one would expect from a bell curve. This means that the most likely outcome may be much less serious than the expected value of the harm and that the variance, which measures the degree of risk against which one might want insurance, may be large compared to the expected value. The remainder of this paper explores how this insight might affect our thinking about environmental policy.

[45] *See* BENOIT B. MANDELBROT, THE FRACTAL GEOMETRY OF NATURE 337-38 (1983).

II. RETHINKING TRADITIONAL APPROACHES TO ENVIRONMENTAL UNCERTAINTY

Complexity theory has had a limited impact on our thinking about environmental problems but scholars and policymakers have long struggled with the problem of environmental uncertainty. This section will examine three leading approaches to uncertainty and consider the implications of statistical power laws for each one.

A. Risk Assessment

Risk assessment is the technique currently favored by American regulators. After identifying a hazard, risk assessment involves estimation of the dose-response curve and of exposure levels in order to determine the level of danger.[46] The process can be illustrated with the appraisal of cancer risks. Two major methods are currently used for estimating cancer risks.[47] The first is based on epidemiology, that is, statistical studies of human populations. These studies are easiest to perform when identifiable occupational groups are exposed to high levels of some substance. The basic idea is simply to compare cancer rates in the occupational group with those in the general population. In practice, such comparisons are harder to make than they sound. Since cancer does not appear until decades after exposure, researchers must identify workers who were exposed many years ago. Such workers usually differ from the general population in other ways such as dietary habits, smoking or alcohol use, further complicating the analysis. Finally, it is necessary to extrapolate from the high levels of typical earlier occupational exposures to the usually much lower levels of current environmental exposures. This process involves much uncertainty. Alternatively, epidemiologists can study how disease levels vary with risk exposure among members of the general population. This eliminates the need for extrapolating to different dose levels, but such studies are expensive and difficult to interpret.

The other major method for estimating cancer risks involves animal studies. As these are controlled experiments, confounding factors are

---

[46] *See* John S. Applegate & Celia Campbell-Mohn, *Risk Assessment: Science, Law and Policy*, 14 NAT. RES. & ENVT. 219, 220 (2000); Alon Rosenthal et al., *Legislating Acceptable Cancer Risk from Exposure to Toxic Chemicals*, 19 ECOLOGY L.Q. 269, 278 (1992).

[47] For a detailed review of EPA's methods for assessing risks, see U.S. GEN. ACCOUNTING OFFICE, ENVIRONMENTAL PROTECTION AGENCY: USE OF PRECAUTIONARY ASSUMPTIONS IN HEALTH RISK ASSESSMENTS AND BENEFITS ESTIMATES (Oct. 2000), *available at* http://www.gao.gov (last visited Sept. 19, 2003).

eliminated. But there are other problems: the experiments are expensive so researchers must use small groups of laboratory animals. This requires the use of high doses since only a very large risk will show up with so few animals. Again, estimation of the dose-response curve is necessary. An additional problem is that a substance that causes harm in one species, such as rats, might not do so in another species, such as humans.[48]

EPA's risk assessment methodology has been controversial. In particular, EPA has generally assumed that risk is proportional to exposure. Critics argue that this straight-line method greatly overestimates the effects of very low doses.[49] These critics argue that using conservative risk assessments overstates the expected benefits of regulation by overestimating mean risks. There are sounder ways to be "conservative and protective of health than distorting the true values of risk."[50] Still others argue for a "U-shaped curve" in which very small doses may have a beneficial health effect. This effect, known as "hormesis," might sometimes support relaxation of risk regulations but may also support more stringent regulation because of the possibility of obtaining health benefits by mandating "sub-threshold" doses.[51] Other studies suggest that one-time exposure to some chemicals may cause cancer, even at doses too small to create other toxic effects.[52] Thus the dose-response curve remains something of a puzzle.

These problems with risk assessment can have dramatic consequences.[53] For instance, in the case of one pesticide, one analyst estimated a mortality level of twenty-seven over a seventy year period but the statistical confidence interval turned out to range from zero to sixty thousand.[54] Similarly, estimates of cancer risks to workers exposed to benzene ranged from one to twenty-five per thousand workers,

---

[48] These problems in risk assessment are discussed in McGarity, *supra* note 4, 2341.

[49] *See* Chlorine Chemistry Council v. EPA, 206 F.3d 1286 (D.C. Cir. 2000) (faulting EPA for failing to take into account nonlinear effects of chloroform in drinking water).

[50] JAMES T. HAMILTON & W. KIP VISCUSI, CALCULATING RISKS? THE SPATIAL AND POLITICAL DIMENSIONS OF HAZARDOUS WASTE POLICY 61 (1999).

[51] *See* Frank B. Cross, *Incorporating Hormesis in Risk Regulation*, 30 ENVTL. L. REP. 10778 (2000).

[52] *See* Edward J. Calabrese & Robyn Blain, *A Single Exposure to Many Carcinogens Can Cause Cancer*, 28 ENVTL. L. REP. 10, 254 (1998); Jocelyn Kaiser, *Panel Cautiously Confirms Low-Dose Effects*, 290 SCI. 695 (2000).

[53] *See* Wendy E. Wagner, *Congress, Science, and Environmental Policy*, 1999 U. ILL. L. REV. 181 (1999).

[54] THOMAS MCGARITY, REINVENTING RATIONALITY: THE ROLE OF REGULATORY ANALYSIS IN THE FEDERAL BUREAUCRACY 135 (1991).

depending largely on disputes about the implications of some key studies from Turkey.[55] Thus, as two recent authors put it:

> Risk assessment has been controversial because it is a complex, judgment-filled process. It is not, as some would suggest, a simple matter of scientific observation. The effects of concern — low-probability risks of injury that may occur long after exposure occurs — are not directly observable.... Ironically, the high degree of uncertainty concerning the mechanisms of chronic diseases and dangerous levels of exposure were reasons for adopting risk assessment, yet today the uncertainties operate as a serious limitation on the ability of risk assessment to quantify risk.[56]

With a bit of hyperbole, one expert is said to have compared risk assessment to a method allegedly used to weigh hogs in Texas: "Down there, they put the hog in one pan of a large set of scales, put rocks in the other pan, one by one, until they exactly balance the weight of the hog. Having done that very carefully, they guess how much the rocks weigh."[57] Though risk assessment may not be quite the exercise in arbitrariness that this description suggests, it is nevertheless true that uncertainties plague risk analysis.

Even once we have made a determination of the level of risk, determining the correct response is not easy. Advocates of risk assessment often endorse cost-benefit analysis as the ultimate standard of decision making. By now, a huge scholarly literature exists on the practicality and ethics of cost-benefit analysis in environmental regulation.[58] Consideration of that debate in this essay would take us far afield. Even staunch devotees of cost-benefit analysis admit that "the thought that science and economics, taken together, can produce bottom lines to be mechanically applied by regulatory agencies" is a "false promise."[59]

---

[55] *See* JOHN GRAHAM ET AL., IN SEARCH OF SAFETY: CHEMICALS AND CANCER RISK 164-65, 177 (1988).

[56] Applegate & Campbell-Mohn, *supra* note 46, at 220-21.

[57] STEPHEN BREYER, BREAKING THE VICIOUS CIRCLE: TOWARD EFFECTIVE RISK REGULATION 108 n.58 (1995).

[58] For recent contributions to this debate, see Frank Ackerman & Lisa Heinzerling, *Pricing the Priceless: Cost-Benefit Analysis of Environmental Protection*, 150 U. PENN. L. REV. 1553 (2002); Steve P. Calandrillo, *Responsible Regulation: A Sensible Cost-Benefit, Risk Versus Risk Approach to Federal Health and Safety Regulation*, 81 B.U. L. REV. 957 (2001); George Keating, *Pressing Precaution Past the Point of Cost-Justification*, 56 VAND. L. REV. 653 (2003).

[59] Cass R. Sunstein, *The Arithmetic of Arsenic*, 90 GEO. L.J. 2255, 2258 (2002).

Another significant source of uncertainty relates to the indirect effects of regulation. Requiring use of a flame retardant in children's pajamas may serve its intended purpose of saving lives from fires but may also turn out to pose a cancer risk.[60] Similarly, banning one hazardous substance may result in the use of other potentially hazardous substitutes. Thus, many analysts call for the use of a risk-risk analysis to determine what new risks may be created by a regulation.[61] On the other hand, efforts to control a particular risk may have serendipitous benefits.[62] In its effort to reduce urban air pollution, EPA mandated drastic reductions in carbon monoxide emissions, which had the entirely unexpected benefit of saving thousands of lives from accidental carbon monoxide poisoning and suicide.[63] Similarly, regulations of other air pollutants can cause switches from coal to cleaner fuels like natural gas, thereby reducing carbon dioxide emissions and helping to combat global warming.[64]

A recent debate over arsenic regulation highlights some of the major issues regarding risk assessment. In examining the potential health benefits of an EPA drinking water regulation, Cass Sunstein concluded that the number of lives saved annually could be "as low as 5 or as high as 112" and that the "annual monetized benefits of the proposed standard" could be "as high as $1.2 billion or as low as $10 million!"[65] Part of the uncertainty involves the shape of the dose-response curve[66] and another stems from the difficulty of interpreting studies of the effect of arsenic on Taiwanese villagers.[67] Sunstein advocated a middle-of-the-road choice of estimates.[68] In response, Tom McGarity argued that EPA's methodology was entirely defensible and he contended that a contrary report on which Sunstein relied was actually "unbalanced and reflected a clear ideological bias against health and safety regulations."[69] In particular, McGarity criticized that report as misunderstanding the

---

[60] *See* JOHN D. GRAHAM & JONATHAN B. WIENER, RISK VERSUS RISK: TRADEOFFS IN PROTECTING HEALTH AND THE ENVIRONMENT 15 (1995).

[61] *See id.*; Cass R. Sunstein, *Health-Health Tradeoffs*, 63 U. CHI. L. REV. 1533 (1996).

[62] *See* Samuel J. Rascoff & Richard L. Revesz, *The Biases of Risk Tradeoff Analysis: Towards Partiy in Environmental and Health-and-Safety Regulation*, 69 U. CHI. L. REV. 1763 (2002).

[63] *Id.*, at 1766, 1807-08.

[64] *Id.* at 1826-31.

[65] Sunstein, *supra* note 59, at 2258.

[66] *Id.* at 2276, 2282.

[67] *Id.* at 2270, 2283.

[68] *Id.* at 2296.

[69] McGarity, *supra* note 4, at 2356.

mechanisms of arsenic metabolism and adopting a "simplistic" model without foundation in the data.[70] Another response to Sunstein by Lisa Heinzerling attacked his use of cost-benefit analysis rather than risk estimates.[71] Besides defending cost-benefit analysis in general, Sunstein responded by asking what alternatives to risk assessment could possibly make sense:

> McGarity thinks that the largest lesson of the arsenic controversy involves the "daunting scientific uncertainties" that plague cost-benefit analysis. In view of these uncertainties, he thinks that cost-benefit analysis is a matter of "frequently preposterous and always manipulable number spinning." He has a point. But it need not be a matter of "spinning." We might try instead to identify the likely range of effects, and when the range is large, we might want to know why the benefits might be small and why they might be big. If we are choosing among several levels of protection, what should we do instead? Guess? Flip a coin?[72]

Complexity theory does provide some insights into this question — not definitive answers but at least better advice than flipping a coin. The presence of statistical power laws supports the use of conservative methods of assessing risk. To be more specific, suppose that we are designing a procedure to identify any proposal posing a significant risk, with significance defined as some specific risk level such as one in ten thousand. The "proposal" might be to approve the marketing of a chemical, to go ahead with a government project, or anything else of environmental relevance. The harm in question might be cancer, or some other health effect, or an ecological impact. The only assumption is that among the relevant set of proposals, harmful effects follow a power-law distribution. If so, conservative test procedures may be warranted.

We might consider a test procedure to be conservative if it is designed to identify nearly all dangerous proposals but does so at the cost of mis-identifying innocent proposals as dangerous — just to be on the safe side, one might say. By adjusting the procedure, we can lower the chances of missing a harmful proposal — a false negative — but only by increasing the number of times we wrongly label a proposal as harmful — a false positive. The ratio of true positives to false positives provides one measure of how conservative the test is. For example, a 1:1 ratio means that half of the proposals identified by the test are dangerous, but

[70] *Id.* at 2361-62.

[71] Lisa Heinzerling, *Markets for Arsenic*, 90 GEO. L.J. 2311 (2002).

[72] Cass R. Sunstein, *In Praise of Numbers: A Reply*, 90 GEO. L.J. 2379, 2384 (2002).

a 1:4 ratio means that only twenty percent are truly dangerous. Thus a conservative approach deliberately over-regulates, minimizing the chances of missing a true threat but at the price of regulating many harmless proposals.

If the likelihood that a given proposal is harmful follows a power law, then the ideal test will probably be at least somewhat conservative.[73] With a power curve, missing true positives can be very costly. Thus, we are likely to want a test that mislabels some innocuous proposals but has a good chance of identifying dangerous ones. We will want to treat proposals that cross the threshold as if their risk level was actually higher than the threshold.

A quantitative example may be helpful. Recall the earlier example of a task whose duration follows a power law with an average expected duration of three days. If the task is known to take at least five days, then the expected duration turns out to be fifteen days.[74] Let us suppose that the same power law applies to mortality rates for chemicals drawn from some pool of regulated substances: the average mortality is three but if the rate is known to be at least five, then the expected mortality becomes fifteen. Our regulatory strategy is as follows:

> 1. We have a test for dangerous chemicals, let's say using animals. When the test comes out positive, then with probability, p, the mortality rate is at least five; with probability 1-p, the test result is meaningless, perhaps because of differences in toxic responses between animals and the test animals.
>
> 2. If the test comes out positive, we ban the substance and substitute another drawn at random from the same pool (the comparative risk part of the analysis). The substitute is more expensive, with a cost equivalent to an additional two deaths.

How conservative should we be? At what level of p is it worth banning the substance? We might think that the normal "preponderance of the

[73] I am not aware of any formal studies of the distribution of environmental risks among various substances. It would seem, however, that there are a large number of substances that pose little or no risk at actual exposure levels, and a small number (such as asbestos and cigarettes) that pose huge risks. This pattern would fit with a power law. Moreover, given the complexity and probable nonlinearity of the biological processes involved, complexity would seem applicable, giving a power law some possible theoretical appeal. As noted in the introduction, this article can be considered, to some extent, as being in the nature of a thought experiment about the policy implications of some important theoretical developments. But it will be some time until we know whether those theoretical developments have solid empirical support.

[74] *See supra* text accompanying note 41.

evidence" or fifty percent standard should apply, or perhaps even a greater burden of proof. When it works, the test is supposed to indicate if the mortality rate is at least five. At a mortality rate of five, we are indifferent between banning the substance and using the substitute (which has an expected mortality rate of three plus an economic cost equal to two). So the only reason to ban the substance is to hedge against the possibility that the actual risk level is even higher than five. We need to balance this against the fact that when the test does not work, a ban is really bad, as it is expected to save no lives but imposes an economic cost equivalent to two additional deaths. It would seem that a very reliable test might be required or, at the very least, we would want to require a test that is reliable more often than not. In reality, a much more conservative approach is warranted.

If we do not ban the substance, there is a probability, p, that the test is meaningful and if it is, the expected mortality rate is fifteen. There is also a probability of 1-p that the test is meaningless and that the expected mortality rate is three, the same as that for the entire pool of chemicals. Hence, the expected mortality when the test is positive is $15p + 3(1-p)$. If we ban the substance, the expected mortality from the substitute is three and we incur an additional economic cost equivalent to two, so the total harm is equivalent to five. Hence, we should ban the substance if $15p + 3(1-p) > 5$, or equivalently, if $p > 1/6$ (approximately 16.6%). In other words, we should ban the substance even when there is only a 16.6% chance that the positive test result is valid. This is quite a conservative risk assessment: we ban the substance even though only one out of every six test results is valid and even though a valid result proves only that the harm is at or above the break even point.

To switch from the environmental context, suppose that the proposal is to allow a particular passenger to go past the security checkpoint at an airport. Any standard for stopping passengers will inconvenience some innocent passengers. Nevertheless, it is worth inconveniencing a lot of innocent travelers in order to catch any single terrorist because the expected harm from a single terrorist is much higher than the inconvenience to any single traveler. The risk distribution for travelers does not follow a bell curve; rather, the large majority of travelers will cause no harm at all while a tiny number of terrorists will cause disastrous outcomes. If we have designed the system so that the number of innocent travelers stopped is equal to the number of terrorists stopped, we should probably change the test so as to sweep with a wider net; it would be worth stopping a lot more travelers simply to increase the chances of catching one more terrorist. Of course, at some point it becomes counterproductive to make the net any wider, but we will not reach this point until we are stopping many more travelers than terrorists. Thus the optimum screening procedure for terrorists is quite conservative.

This hypothetical also shows why it may be a mistake to worry too much about comparative risks. Suppose that whenever we stop a traveler, another traveler gets to pass through security without being checked. This is definitely a cost, since that traveler might also be a terrorist and will now escape detection. But the odds are extremely small that a randomly chosen traveler is a terrorist whereas the odds are much higher among the people being stopped. Because the risk level for the detained group is so much higher than the risk level for the average traveler, the cost of letting through another traveler without testing is much smaller than the benefit of administering the test.[75]

Similarly, if environmental risks follow a power law, then the expected risk level of the harmful proposals is quite high.[76] Even though many of the proposals are harmless, the others will be statistically much more dangerous than the threshold we have established as significant. On the other hand, when we switch to a substitute proposal, we are drawing out of the entire pool of proposals, where the average level of risk should be substantially lower. So this is a cost, just like letting an additional traveler slip through without testing, but it is a cost that is likely to be far lower than the benefit of blocking a proposal which is known to exceed the risk threshold. Thus, for environmental risks that follow a power law, the EPA may be justified in using conservative tests and in de-emphasizing comparative risk analysis.

In applying these insights, it is obviously quite important to know whether the risk in question follows a power law. Such a power law is not likely to exist when the dynamic process is known to be linear, which may eliminate some cases. Otherwise, we can use either of two techniques to determine whether a power law applies. First, we can use direct empirical evidence, using a log-log plot of outcomes. (For a power law we have: $y = kx^{-a}$. Taking logs of both sides gives us: $\log y = \log k - a \log x$, so a log-log regression should be a good fit.) Alternatively, we

[75] Of course, terrorists might make a practice of traveling in pairs to take advantage of the "free pass" for the second person, but potentially hazardous substances cannot make strategic responses to our regulatory techniques.

[76] An additional caveat: it is possible that even with the least conservative test, the likelihood of a true positive is so small compared with the costs of false positives that no testing at all is warranted. But if we are going to test at all, we will want a test that produces a high proportion of false positives.

can create the best possible mathematical or computer model of the process and determine whether the model exhibits a power law. In some situations, we may know that the process is nonlinear but be unsure about whether a power law applies. In such situations, the best we can do is to hedge our bets by being a little more conservative in our risk assessments.

B. The Worst Case Scenario

An environmental impact statement does not dictate the substance of regulatory decisions but is at least supposed to force the agency to take a "hard look" at the relevant factors.[77] At one time, agencies were required to deal with uncertainty by discussing the "worst case" scenario. The history and implementation of this regulation is instructive.

In 1978, the Council on Environmental Quality, the executive agency supervising implementation of the EIS requirement, provided direction to agencies on how to deal with scientific uncertainty.[78] The regulation applied when there were "gaps in relevant information or scientific uncertainty" about a project's environmental impacts.[79] When such information was obtainable at reasonable cost, the agency was instructed to obtain it but otherwise the agency was told to pursue the following course:

> If (1) the information relevant to adverse impacts is essential to a reasoned choice among alternatives and is not known and the overall costs of obtaining it are exorbitant or (2) the information relevant to adverse impacts is important to the decision and the means to obtain it are not known (e.g. the means for obtaining it are beyond the state of the art) the agency shall weigh the need for the action against the risk and severity of possible adverse impacts were the agency to proceed in the face of uncertainty. If the agency proceeds, it shall include a worst case analysis and an indication of the probability or improbability of its occurrence.[80]

In a 1981 guidance document, CEQ explained this rule as mandating "reasonable projections of the worst possible consequences of a proposed action."[81] As an illustration, CEQ said that where a proposed water

[77] *See* Robertson v. Methow Valley Citizens Council, 490 U.S. 332 (1989).

[78] *See* Edward A. Fitzgerald, *The Rise and Fall of Worst Case Analysis*, 18 U. DAYTON L. REV. 1 (1992).

[79] 40 C.F.R. § 1502.22 (1991).

[80] *Id.* § 1502.22(b) (1991).

[81] Vicki O. Masterman, *Worst Case Analysis: The Final Chapter?*, 19 ENVTL. L. REP.

quality facility would have an unknown impact on juvenile fish, the EIS must include "the possibility of the loss of the commercial or sport fishery."[82] Note that agencies were not directed to avoid taking action in the face of uncertainty but rather to engage in a balancing test weighing the need for the action against the risk. Worst case analysis was a disclosure requirement, not a decision technique.

Sierra Club v. Sigler[83] was the leading case to apply the worst case requirement. The case involved a controversial proposal to allow oil tankers to operate in a wildlife estuary near the Port of Galveston.[84] The EIS concluded that the project would not significantly increase the probability or likely harm of an oil spill.[85] The relevance of oil spills to the decision was unquestioned and the parties agreed that "an analysis of a supertanker oil spill involving a total cargo loss beyond 24 hours after it occurs is beyond the state of the art."[86] The agency had thought this possibility was too remote to warrant discussion. Relying on CEQ's 1981 guidance document, however, the Fifth Circuit held that the EIS was invalid because it "failed to discuss the 'catastrophic impact' of a total cargo loss by a supertanker in the Bay" and the court faulted the agency for failing to consider "that impact and the probability of its occurrence" in deciding to proceed.[87]

The worst case requirement was criticized as being excessively pessimistic and too intrusive on agency discretion.[88] In its 1981 guidance document, CEQ explained the rule as mandating "reasonable projections of the worst possible consequences of a proposed action."[89] In 1983, CEQ proposed (but later withdrew) a guidance document that would have required a worst-case analysis only when a risk crossed an "initial threshold of probability" and was reasonably foreseeable but its consequences were uncertain.[90] In the Fifth Circuit's view, the fact that a risk was extremely remote was relevant in assessing its ultimate import for the final decision but not relevant in deciding whether to include a

---

10026, at 10027 n.14 (1989).

82 *Id.*

83 Sierra Club v. Sigler, 695 F.2d 957 (5th Cir. 1983).

84 *Id.* at 962.

85 *Id.* at 968.

86 *Id.* at 973.

87 *Id.* at 972.

88 *See* Note, *Federal Agency Treatment of Uncertainty in Environmental Impact Statements Under the EPA's Amended NEAP Regulation § 1502.22: Worst Case Analysis or Risk Threshold?*, 86 MICH. L. REV. 777, 807-09 (1988).

89 Masterman, *supra* note 81, at 10027 n.14.

90 *Id.*

discussion of it as the worst-case scenario.[91] The court hastened to add, however, that "while remoteness of a possible occurrence does not permit disregarding it in such circumstances as these, where a real possibility of the occurrence has been proved and a database for evaluating its consequences established, the Corps need not concern itself with phantasmagoria hypothesized without a firm basis in evidence and the actual circumstances of the contemplated project, or with disasters the likelihood of which is not shown to be significantly increased by the carrying out of the project."[92]

After withdrawing the 1983 proposal, CEQ called for public comment on possible methods of dealing with uncertainty. It received a laundry list of complaints about the worst case requirement such as "the limitless nature of the task of conjuring the worst possible case," "the lack of expert support for worst-case analysis in the growing field of risk analysis," and the "minimal value of fanciful worst-case analyses to federal decision-makers who must balance a full range of proven competing interests."[93] CEQ then issued a new regulation dealing with uncertainty, replacing the worst-case scenario requirement. The new regulation, which is still in effect, tells agencies that when important information is not available at a reasonable cost, they must include in the EIS:

> (1) A statement that such information is incomplete or unavailable; (2) a statement of the relevance of the incomplete or unavailable information to evaluating reasonably foreseeable significant adverse impacts on the human environment; (3) a summary of existing credible scientific evidence which is relevant to evaluating the reasonably foreseeable significant adverse impacts on the human environment; and (4) the agency's evaluation of such impacts based upon theoretical approaches or research methods generally accepted in the scientific community.[94]

The regulations define "reasonably foreseeable" to include impacts "which have catastrophic consequences, even if their probability of occurrence is low, provided that the analysis of the impacts is supported by credible scientific evidence, is not based on pure conjecture, and is within the rule of reason."[95]

---

[91] *Sigler*, 695 F.2d at 974.

[92] *Id.* at 975 n.14.

[93] Masterman, *supra* note 81.

[94] 40 C.F.R. § 1502.22(b) (2003).

[95] *Id.*

It should be noted that, although the new regulation avoids the term "worst case" and calls for a broader discussion of potential risks, it does still call for discussion of low-probability catastrophes. In effect, it defines "worst case" in terms of the rule of reason rather than completely eliminating the worst case requirement.

The Supreme Court upheld the new regulation in *Robertson v. Methow Valley Citizens Council*.[96] In response to a Forest Service decision to allow construction of a private ski resort, the state game department had "voiced a special concern about potential losses to the State's large migratory deer herd, which uses the Methow Valley as a critical winter range and as its migration route."[97] The state agency projected a possible 50% reduction in the herd.[98] The Forest Service was more optimistic but admitted that off-site development caused by the project might "noticeably reduce" the herd.[99] Although the court of appeals held that the EIS was invalid because it failed to put forward an explicit worst-case scenario, the Supreme Court held that the CEQ's current regulation was a reasonable interpretation of the statute.[100] Hence, agencies were no longer required to conduct an explicit worst-case analysis after the new regulation went into effect.

Complexity theory has mixed implications for worst-case analysis. On the one hand, a power law precludes the possibility of a genuine worst case — there are always even worse, though even less likely, cases to worry about. So critics of worst-case analysis were right to worry about the arbitrariness of selecting a single "worst" case. On the other hand, one characteristic of power laws is that the unlikely events on the right tail of the curve have a strong cumulative effect. If we focus only on what seem to be reasonably likely outcomes, we overlook the statistical possibility of nasty surprises. Worst-case analysis can be a useful reminder that through a string of unlikely coincidences, things may go very wrong indeed. Despite the tiny likelihood of any one such freakish outcome, the total spectrum of extreme outcomes may deserve serious weight in the decision. Consideration of the worst cases or, more accurately, of a spectrum of possible "worse" cases, can compensate for the tendency to focus too heavily on the likely outcomes of an action and dismiss speculation about possible disasters. The CEQ's current

---

[96] Robertson v. Methow Valley Citizens Council, 490 U.S. 332 (1989).

[97] *Id.* at 342.

[98] *Id.*

[99] *Id.* at 343.

[100] *Id.* at 354-55.

regulation, particularly the requirement that unlikely outcomes be considered, seems to strike an appropriate balance in requiring consideration of foreseeable disasters even if those outcomes seem highly unlikely.

C. *The Precautionary Principle*

The European Union has emphasized another approach to dealing with uncertainty: the precautionary principle. This principle has been explained on the basis of risk aversion or skepticism about the environment's ability to tolerate damage.[101] The precautionary principle now also appears as part of the Rio Declaration on international environmental law. Principle 15 of the Declaration states:

> In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.[102]

The precautionary principle is now found in a variety of other international environmental agreements, such as conventions on ozone, global climate and biodiversity.[103] It has also been adopted by Germany as a guide to environmental policy and has been invoked by courts in Canada, Pakistan, and India.[104] The precautionary principle served as the basis for the EU's effort to regulate the use of genetically modified organisms in foods.[105]

The precautionary principle is controversial. There seem to be three main criticisms. The first is its vagueness. Chris Stone observes that the principle is vague in part because of the nature of international diplomacy. Nevertheless, he finds it "increasingly frustrating that there is no convergence as to what it means, or as to what regions of action

---

[101] *See* DANIEL FARBER, ECO-PRAGMATISM: MAKING SENSIBLE ENVIRONMENTAL DECISIONS IN AN UNCERTAIN WORLD 170 (1999).

[102] *Rio Declaration on Environment and Development, Report of the United Nations Conference on Environment and Development*, G.A. Res. 48/190, 48 U.N. GAOR Supp. No. 49 at 167, U.N. Doc. A/48/49 (1992), *quoted in* DAVID HUNTER, JAMES SALZMAN, & DURWOOD ZELKE, INTERNATIONAL ENVIRONMENTAL LAW AND POLICY (2d ed. 2002).

[103] HUNTER, SALZMAN & ZELKE, *supra* note 102, at 410.

[104] *Id.* at 410-11. On the Canadian experience, see Juli Abouchar, *The Precautionary Principle in Canada: The First Decade*, 32 ENVT. L. RPTR. 11407 (2002).

[105] HUNTER, SALZMAN & ZELKE, *supra* note 102, at 407.

(environment, public health) it is supposed to apply."[106] In some formulations, the precautionary principle is seemingly a mandate to halt activities when a sufficient level of risk appears, whereas in others it operates to create a presumption against activities potentially harmful to the environment, placing the burden of proof on the advocates of those activities.[107] But none of these formulations is precise, and Stone doubts whether any general rule more specific than "be careful" can be formulated.[108]

A second criticism is that government intervention creates risks of its own.[109] Recall the earlier example of the flame-retardant for children's pajamas that turned out to pose a cancer risk.[110] If the effects of regulation are also uncertain and present unforeseen risks to health and environment, then the precautionary principle seems to turn against itself, suggesting that we should not proceed with environmental regulations until we can pin down their effects. As Sunstein explains:

> There is an obvious difficulty with the precautionary principle: Both regulation and nonregulation will often give rise to risks; if so, the principle would seem to be paralyzing, forbidding stringent regulation, inaction, and everything in between. Consider, for example, the case of genetic engineering of food. The precautionary principle might seem to call for stringent regulation of genetic engineering, on the theory that this technology contains at least some risk of causing ecological harm. But such regulation would also create risks of adverse effects, simply because genetic engineering holds out a prospect of producing ecological and health benefits. The precautionary principle would seem both to require and to forbid stringent regulation of genetic engineering. The same can be said for many activities and processes, such as nuclear power and nontherapeutic cloning, simply because risks are on all sides of the situation.[111]

---

[106] Christopher D. Stone, *Is There a Precautionary Principle*, 31 ENVT. L. RPTR. 10790, B (2001).

[107] *Id.* at B.

[108] *Id.* As we will see, however, Stone does have some suggestions for dealing with uncertainty.

[109] *See* Jonathan H. Adler, *More Sorry Than Safe: Assessing the Precautionary Principle and the Proposed International Safety Protocol*, 35 TEX. INT. L.J. 194 (2000); Frank B. Cross, *Paradoxical Perils of the Precautionary Principle*, 53 WASH. & LEE L. REV. 851, 872 (1996).

[110] *See supra* text accompanying note 60.

[111] Cass R. Sunstein, *Probability Neglect: Emotions, Worst Cases, and Law*, 11 YALE L.J. 61, 93 (2002).

Adding force to the first criticism, this critique argues that the principle is not only vague but also incoherent, since it always, or at least often, generates conflicting directions.

The third criticism adds a charge of irrationality against the precautionary principle. Sunstein argues that when the precautionary principle "seems to offer guidance," it is "often because of the operation of probability neglect," meaning the cognitive incapacity of individuals to attend to the relevant risks.[112]

Considerable debate surrounds these criticisms. The first criticism, based on the principle's vagueness, has prompted various attempts to give it greater content with reference to avoiding irreversible actions, keeping options open, and providing insurance against dangerous risks.[113] Alternatively, some supporters argue that the principle requires a kind of case-by-case, common law development.[114] The second criticism, regarding the existence of risks on both sides of regulatory decisions, is at least partly countered by noting that regulatory decisions may also have unanticipated benefits.[115] The third criticism, as it turns out, may be backwards: a good argument can be made that the precautionary principle is needed to counter defects in the ways people process probability information; rather than being part of the problem of limited human rationality, the precautionary principle may be part of the cure.[116] At this stage, the academic debate is far from settled.

Complexity theory again provides some illumination. We have already seen that it supports some elements of precaution such as the use of conservative risk estimates and consideration of high-damage and low-probability outcomes (the "worst case" scenario). But complexity theory also drives home the importance of risk aversion. We saw earlier that a power law function can have a very large, even an infinite variance.[117] This means that insuring against risks is not merely a

---

[112] *Id.* at 94. Sunstein further elaborates his critique in Cass R. Sunstein, *Beyond the Precautionary Principle*, 151 U. PENN. L. REV. 1003 (2003).

[113] *See, e.g.*, Stephen Charest, *Bayesian Approaches to the Precautionary Principle*, 12 DUKE ENVTL. L. & POL'Y F. 265 (2002); Christian Gollier, Bruno Jullien, & Nicolas Treich, *Scientific Progress and Irreversibility: An Economic Interpretation of the "Precautionary Principle,"* 75 J. PUB. ECON. 229 (2000); W. David Montgomery & Anne E. Smith, *Global Climate Change and the Precautionary Principle*, 6 HUM. & ECOLOGICAL RISK ASSESSMENT 399 (2000); Stone, *supra* note 106.

[114] *See* Stephen Toulmin, *The Case for Cosmic Prudence*, 56 TENN. L. REV. 29 (1998).

[115] *See supra* text accompanying notes 62-64.

[116] DAVID A. DANA, A BEHAVIORAL ECONOMIC DEFENSE OF THE PRECAUTIONARY PRINCIPLE 1315 (2003).

[117] *See surpra* text accompanying note 45.

secondary consideration in decision making. Rather, heavy investment in insurance or risk diversification will often be warranted.

The significance of this factor depends on the specific context, and it seems especially important when environmental problems have broad social impacts. We can provide insurance to individuals who are affected by more targeted risks, spreading the costs across society either through private markets or government safety nets. Risks that affect society as a whole are less easily insured. The alternatives are to diversify the risk, trading one macro-risk for numerous micro-risks, or to make substantial investments to reduce the expected level of harm, even knowing that there is a strong chance that the risk would not materialize anyway. The idea that insurance and risk aversion are relevant to risk management is by no means new. What complexity theory does is highlight this connection by demonstrating that risk premiums may be much higher than one would expect with a more conventional statistical distribution.

What of the point that risks are often present on both sides of a decision, as much when we try to solve a problem as when we ignore it? Whether this is true depends in part on the nature of the action in question. For example, we saw earlier that it may be wise to eliminate a known carcinogen even if the safety of the substitutes is unknown; not only have we diversified the risk but we may even have lowered the expected level of harm. Moreover, uncertainties may not be symmetrical; we may have a much better grasp of the potential economic impact of reducing the use of fossil fuels than we have of the dynamics of global climate. Thus, the possibility of offsetting risks deserves consideration, but we should not take for granted that uncertainty weighs equally heavily on both sides of the decision.

Complexity theory may add some specificity to the precautionary principle or at least establish a less ambiguous subrule. The subrule says something like the following:

> When an environmental problem involves a complex dynamic system and seems likely to follow a power function, insurance should become a major factor in decision-making. When the problem involves broad societal impacts that cannot be easily handled by public or private risk-sharing mechanisms, it is worth making substantial investments to hedge against the possibility of disaster.

A possible example may be provided by global warming. If the likelihood of adverse impacts follows a power law, then the insurance function looms large. If we knew that major impacts would be regionalized, countries might conceivably pool their risks, but we cannot be sure of how regionalized the impacts will be, and international insurance for such huge losses may be inadequate. Hence, it may be worth making very substantial investments to prevent global warming even if the expected dollar harm of global warming is significantly less than the amount of the investment in precautionary measures. The problem is that the variance may be extremely high. It is true that the package of measures needed to ameliorate climate change have risks of their own, but their total expected harm is probably smaller and diversification may be a wise strategy when the alternative risk involves long-term changes to global ecology.

CONCLUSION

As we have seen, complex dynamic systems can have surprising attributes, some of which are captured by power laws. Where these power laws hold sway, our usual statistical approaches may be misleading. The expected harm may be much higher than the midpoint of the range (the statistical median) or the most likely level of harm (the statistical mode). The variance in outcomes may be enormous. If we know only that a risk passes a certain threshold, its expected value will be much worse than the threshold. These characteristics support various precautionary approaches to risk management, including conservative risk assessment, analysis of low probability catastrophes, and payment of high premiums for social insurance.

We need better information than we currently possess about which risks are subject to power laws. It seems plausible that some important environmental risks fall into this category, but we have no reason to think that all of them do. Moreover, as we come to better understand the dynamics of a system, we may be able to short-circuit a power law by moving from precaution to adaptive management — learning as we observe the system's responses to experimental changes and using the new information to steer away from extreme consequences. Power laws are of the most concern when we will be unable to exercise this kind of continuing control, allowing harms to snowball over time.

Most of us are not statisticians but the fact that we are prone to talk about typical outcomes or plausible scenarios reflects an intuitive sense that probabilities are reasonably well behaved. Complexity theory shows that the usual statistical assumptions may break down in some circumstances, where the chance of nasty surprises becomes a major part of risk analysis. It also suggests some possibilities for dealing with those situations more rigorously. For example, if there are power laws for some or all kinds of carcinogens,[118] we could regulate much more effectively if we could estimate the relevant functions.

In the meantime, the possibility that risks are governed by power laws adds credibility to arguments for precaution. We have no *a priori* reason for assuming that bell curves rather than power laws apply to environmental issues. Rather, we have some basis for thinking otherwise, based on what we know about the dynamics of complex systems and on some preliminary empirical evidence. We should not give way to irrational fears but neither should we equate rationality with a particular form of probability distribution. The world may be considerably more unpredictable than standard statistical analysis would predict and, to the extent that this is true, we need to take appropriate precautions.

---

[118] By this I mean that the number of chemicals presenting any given risk level at ambient concentrations follows a power law, rather than that the dose-response curve for any one carcinogen follows such a law.

***