# Uncertainty

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#### I. Introduction

Consider these appraisals of some urgent public policy issues:

"[I]n particular, the science and economics are particularly sparse precisely where the stakes are highest  $\dots$ "<sup>2</sup>

"We don't even know how much we don't know about the probabilities."<sup>3</sup>

"[D]espite all those risks we can control, the greatest ones remain beyond our control. These are the risks we do not see, things behind the veil."<sup>4</sup>

The first two sentences above relate to climate change; the final one concerns instability in financial markets. All three could equally well have referred to a variety of other critical policy issues such as terrorism.

Our society has sophisticated techniques for analyzing risks that can be modeled and quantified.<sup>5</sup> But other threats – often the most serious ones -- do not fit the paradigm. These threats involve what the economist Frank Knight classified as "uncertainty" (where the likelihood of the peril is non-quantifiable) as opposed to "risk" (where the likelihood

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<sup>&</sup>lt;sup>2</sup> NICHOLAS STERN, THE ECONOMICS OF CLIMATE CHANGE 39 (2007). For a discussion of the debate over the Stern Review, see Daniel H. Cole, *The Stern Review and Its Critics: Implications for the Theory and Practice of Benefit-Cost Analysis*, 48 NAT. RES. J. 53 (Winter 2008).

<sup>&</sup>lt;sup>3</sup> Cole, *supra* note 2, at 76.

<sup>&</sup>lt;sup>4</sup> Richard Bookstaber, A Demon of Our Own Design: Markets, Hedge Funds, and the Perils of Financial Innovation 241(2007).

<sup>&</sup>lt;sup>5</sup> A particularly useful discussion of these methods, focusing on the Environmental Protection Agency (EPA), can be found in NATIONAL RESEARCH COUNCIL, SCIENCE AND DECISIONS: ADVANCING RISK ASSESSMENT (2009).

is quantifiable).<sup>6</sup> This article follows Knight's terminology, using the terms "threat" or "hazard" to cover both categories where necessary. Uncertainty is particularly pernicious in situations where catastrophic outcomes are possible, but conventional statistical tools do not always do well in such situations, as discussed below.

Uncertainty is not the same as complete ignorance. Large bodies of data and theory bear on climate change<sup>7</sup> and financial markets<sup>8</sup> – so it is not as if we are operating completely in the dark. The trouble is that, as the quoted statements indicate, our knowledge about potential catastrophic outcomes is much more limited. As to those more extreme outcomes, we confront grave uncertainty.

All too often, the response to such uncertainty is to ignore the problem in the hope that it will go away or that a solution will turn up on its own. Alternatively, advocates seize on their own version of the true magnitude of the hazard, as if there were no doubt about the facts. Neither approach produces intelligent analysis or sound policy. This Article considers how we could use new advances in economics and decision theory to do better.

Following this introductory Part I, Part II of the Article sets the stage by explaining conventional risk analysis and the alternative approach often used elsewhere in the world. Risk analysis, which assumes that the probability of harm can be quantified with reasonable confidence, is embedded in the U.S. regulatory system.<sup>9</sup> Europeans and others have tended to rely instead on the precautionary principle, a less structured approach that does not require quantification but generally advises against taking action where the risks are unknown.<sup>10</sup> But the precautionary principle has been subject to serious criticism, however, and is difficult to operationalize. Thus, neither the U.S. nor the European approach is satisfactory in cases of uncertainty.

<sup>&</sup>lt;sup>6</sup> FRANK KNIGHT, RISK, UNCERTAINTY AND PROFIT (1921). Uncertainty also played a central role in the thought of John Maynard Keynes. *See* PETER CLARKE, KEYNES: THE RISE, FALL, AND RETURN OF THE 20TH CENTURY'S MOST INFLUENTIAL ECONOMIST 154-157 (2009).

<sup>&</sup>lt;sup>7</sup> See discussion infra Parts IV.A, IV.B.

<sup>&</sup>lt;sup>8</sup> See discussion infra Part IV.E.

<sup>&</sup>lt;sup>9</sup> Quantification of risks is required for cost-benefit analysis, which has been mandated for the past twenty-eight years when the government issues important regulations. Shortly after taking office President Reagan signed Executive Order No. 12,291, 46 Fed. Reg. 13,193 (1981), aimed at improving the efficiency of informal rulemaking by executive agencies. Section 2 prohibits issuance of "major" regulations unless, "taking into account affected industries [and] the condition of the national economy," the potential benefits to society outweigh potential costs, and net benefits are at a maximum. For recent defenses of cost-benefit analysis, see John D. Graham, *Saving Lives Through Administrative Law and Economics*, 157 U. PA. L. REV. 395 (2008); W. Kip Viscusi, *Monetizing the Benefits of Risk and Environmental Regulation*, 33 FORDHAM URBAN L.J. 1003 (2006). For a vigorous critique of the way cost-benefit analysis treats environmental and health risks, see Frank Ackerman & Lisa Heinzerling, *Pricing the Priceless: Cost-Benefit Analysis of Environmental Protection*, 150 U. PA. L. REV. 1553 (2002).

<sup>&</sup>lt;sup>10</sup> See infra text accompanying note 43.

Part III introduces some new techniques for analyzing uncertainty. The most difficult policy issues often involve some chance of catastrophic outcomes, but conventional analysis may underestimate the seriousness of the situation. Economic modeling and policy analysis are often based on the assumption that extreme harms are highly unlikely, in the technical sense that the "tail" of the probability distributions is "thin" – in other words, that it approaches rapidly to zero. Thin tails allow extreme risks to be given relatively little weight. A growing body of research, however, focuses on the possibility of fat tails, which are common in systems with feedback between different components.<sup>11</sup> As it turns out, determining the precise "fatness" of the tails is often quite difficult, which causes models involving fat tails to blur from risk into uncertainty.<sup>12</sup>

Fat tails and uncertainty often go hand in hand. Economic theories of "ambiguity" deal at a more general level with situations where multiple plausible models of reality confront a decision maker.<sup>13</sup> Ambiguity theories are useful in considering systems with fat tails and in other situations where the probabilities are simply difficult to quantify.

Based on ambiguity theory, this Article proposal the " $\alpha$ -precautionary principle" for use when, because of fat tails or otherwise, decision makers cannot quantify risks and face Knightian uncertainty. This principle differs from current conceptions of the precautionary principle by considering both the worst-case and best-case scenarios, rather than focusing merely on uncertainty about harmful outcomes. Thus, the  $\alpha$ -precautionary principle is more nuanced than conventional versions of the precautionary principle while still remaining attentive to possible catastrophic outcomes and simple enough for easy application. For instance, the  $\alpha$ -precautionary principle suggests a highly precautionary approach to the uncertainties surrounding climate change<sup>14</sup> but a less precautionary approach to the uncertainties of nanotechnology.<sup>15</sup>

Thus, one advantage of the  $\alpha$ -precautionary principle is that it provides a way of gauging the degree of appropriate precaution. It also suggests that in some situations, conventional risk assessment is adequate without any special need for precaution. Those situations exist when the probability of harm can be reasonably ascertained, in the sense that we have some confidence in our ability to identify the relevant probability distribution and that the distribution itself is well-behaved (it has a finite mean and variance). There may also be situations where we are not currently in a position to specify that probability distribution but we have good grounds for thinking that we could do so with further research; in those situations, we need to consider the possible strategy of delaying decision while funding the additional research.

<sup>&</sup>lt;sup>11</sup> See infra text accompanying notes 84 to 101.

<sup>&</sup>lt;sup>12</sup> See infra text accompanying notes 102 to 106.

<sup>&</sup>lt;sup>13</sup> See infra text accompanying notes 108 to 121.

<sup>&</sup>lt;sup>14</sup> See infra text accompanying notes 173 to 179.

<sup>&</sup>lt;sup>15</sup> See infra text accompanying notes 213 to 215.

The new techniques involved in this article occupy a middle-space between conventional versions of risk assessment and the precautionary principle. Like the precautionary principle, these techniques do not require assigning precise probabilities when doing so would be inappropriate. But the new techniques do use mathematical tools of various kinds to help decision-makers cope with uncertainty, and in that regard they resemble conventional forms of risk analysis currently used by economics and financial theorists.<sup>16</sup>

Part IV turns to specific regulatory issues – involving climate change, nanotechnology, nuclear waste disposal, and financial markets – in order to see what insights can be gained from these advances in the theory of decision-making.<sup>17</sup> The analytic tools introduced in Part III shed light on these difficult regulatory issues, though they do not provide complete solutions. Different tools turn out to be most helpful in thinking about different problems.<sup>18</sup> It is remarkable, however, that issues as seemingly unrelated as financial market regulation and climate change have deep structural similarities (involving fat tailed distributions and model uncertainty) and are potentially amenable to similar analytic tools.

Problems involving true uncertainty have an inherent intractability.<sup>19</sup> It seems doubtful that there is any way of addressing these problems that does not, in the end, require an act of judgment on the part of the decision maker rather than merely applying a pre-set methodology. But the analysis presented in this article can clarify the choices and provide decision-makers with a coherent process for considering uncertainties.

Admittedly, how to make decisions in the face of model uncertainty is a knotty problem.<sup>20</sup> Given that many of these uncertainties involve urgent societal problems, however, we should be grateful for whatever help we can get in making clear-headed,

 $<sup>^{16}</sup>$  As with all decision-making tools, these tools have their costs, and we must always consider whether the benefits of the tools outweigh the decision-making costs. But in most cases the incremental costs will not be high – if we have already determined that a single distribution has fat tails, or that two different models produce different results, the remaining steps in the analysis are often fairly straightforward.

<sup>&</sup>lt;sup>17</sup> An important caveat is in order. The fundamental research discussed in this article is rapidly developing and work on practical applications is at an even earlier stage. Thus, the conclusions discussed in this article – particularly as they bear on particular issues such as climate change – must be considered preliminary.

<sup>&</sup>lt;sup>18</sup> The models discussed in this article may also have non-regulatory legal applications. For instance, litigation of major cases may involve uncertainty about results that could impact settlement behavior and litigation strategy, in ways relevant to the design of civil procedure rules. Use of ambiguity models in this context might be fruitful.

<sup>&</sup>lt;sup>19</sup> The term "model uncertainty" is sometimes used in this situation, where we have one or more models of the world but are unsure which one is right. Dealing with model uncertainty is widely acknowledged to be difficult. *See* NATIONAL RESEARCH COUNCIL, *supra* note 5, at 105-106 ("One of the dimensions of uncertainty that is difficult to capture quantitatively (or even qualitatively) involves model uncertainty.").

<sup>&</sup>lt;sup>20</sup> See id.

intelligent decisions. Issues like climate change, nuclear power, and financial stability are too important for society to use anything less than the best available analytic tools.

#### **II.** Current Approaches to Environmental Risks and Uncertainties

The regulatory system often addresses probabilistic harms. For instance, we may know that a chemical is a carcinogen, but we may or may not know how many of the people who are exposed will get cancer. Even if we know how many cancer cases to expect, we may be unable to predict which specific individuals will develop the illness. Conventional risk assessment, which is the dominant mode in the United States, requires quantification of probabilities and hence is not well adapted to true uncertainty. The European Union favors the use of the precautionary principle, which does address unquantified possible harms, but functions more as a source of sound advice than a method of analysis. This surveys both approaches as a prelude to discussing new tools for decision making under uncertainty.

# A. Conventional Risk Assessment

We will begin by considering the basics of risk assessment and consider its limitations in cases involving hazards that cannot be readily quantified. As we will see, courts sometimes have reproved courts for ignoring unquantified hazards, sometimes given their blessing as the agency buried its head in the sand, and sometimes have even forbidden agencies to act in absence of quantification.

*1. The Basics.* A quick, albeit superficial, introduction to the standard economic approach to probabilistic events may be helpful for some readers. The standard approach to risk analysis is based on expected utility theory. Application of expected utility theory can be extremely complex, particularly given the difficulty of determining the probability of various outcomes.<sup>21</sup> Since we are largely concerned with situations in which the theory breaks down, however, knowledge of the details is not necessary for present purposes.

We begin with the idea of the expected outcome. The probability that a tossed coin will come up heads is 0.5. Suppose that you can win \$10 if the coin comes up heads, but lose \$5 if it comes up tails. The question is whether to take the bet. If you repeated a bet of this kind many times, on average you'd expect to win \$10 half the time and lose \$5 half the time. So the expected return is  $[(.5 \times 10) - (.5 \times 5)] = 2.50$ . (Imagine doing a hundred coin tosses – you'd expect to win \$10 fifty times and lose \$5 the other fifty, for a net gain of \$250 or on average \$2.50 every time you toss the coin.)

<sup>&</sup>lt;sup>21</sup> Some of the complexities are addressed with an eye to practical implementation in MICHAEL V. FRANK, CHOOSING SAFETY: A GUIDE TO USING PROBABILISTIC RISK ASSESSMENT AND DECISION ANALYSIS IN COMPLEX, HIGH-CONSEQUENCE SYSTEMS (2008). A large literature covers the specific problems of determining the level of risk for toxic chemicals, particularly carcinogen, and considerable controversy continues on this subject. *See* Environmental Protection Agency, *Guidelines for Carcinogen Risk Assessment and Supplemental Guidance for Assessing Susceptibility from Early-Life Exposure to Carcinogens*, 70 FED. REG. 17766 (2005). Some of the practical difficulties in public health studies are explored in Carole Bass, *Solving a Massive Worker Health Puzzle*, SCI. AM., March 2008, at 86.

Thus, if you played this game often enough, on average you'd expect to win \$2.50 each time. This amount is the expected value of the bet.<sup>22</sup> Although cost-benefit analysis can be complex because of the difficulty of determining the probabilities and measuring costs and benefits, conceptually it is fundamentally as simple as deciding what to bet on this coin toss.

We used the term expected utility earlier and this requires a small revision in the analysis. People are often risk averse – that is, they prefer not to gamble.<sup>23</sup> For instance, they may prefer a certainty of losing \$1000 in the form of paying an insurance premium rather than take a 1% chance of losing \$90,000. Yet if you do the arithmetic, you'll see that in expected value terms, the premium costs more than the expected value of the insurance (1 x 1000 = 1000 > .01 x 90,000 = 900). Economists explain this by saying that the utility of an additional dollar declines as wealth rises.<sup>24</sup> This seems intuitively right – a homeless person would presumably care far more than a billionaire about the loss of a dollar.

The existence of insurance can be explained on the basis of risk aversion. Because of declining marginal utility, the dollars in the premium are less "valuable" than the dollars the policyholder would lose from an uninsured loss. Thus, paying a premium for insurance is justified even if the expected value of the insurance is a bit lower than then the premium. The upshot is that what people (individually and as a society) care about is not the expected dollar value of a loss but its expected utility value.<sup>25</sup>

In practice, of course, risk analysis is much more complex than these simple examples. Finding the correct probabilities rarely as easy as it is with coin tosses. Partly because of risk aversion, it is important to know the probabilities associated with the full range of possible harms, not just the most likely level of harm.<sup>26</sup> In other words, we

<sup>&</sup>lt;sup>22</sup> A good introduction to probability theory can be found in JOHN HARTE, CONSIDER A CYLINDRICAL COW: MORE ADVENTURES IN ENVIRONMENTAL PROBLEM SOLVING 1-20 (2001).

<sup>&</sup>lt;sup>23</sup> Risk aversion is explained in STEVEN SHAVELL, ECONOMIC ANALYSIS OF LAW 52 (2004).

<sup>&</sup>lt;sup>24</sup> PAUL KRUGMAN & ROBIN WELLS, ECONOMICS 548 (2d ed. 2009).

<sup>&</sup>lt;sup>25</sup> For further discussion of the techniques used by risk analysts, consult a standard text such as DANIEL M. KAMMEN & DAVID M. HASSENZAHL, SHOULD WE RISK IT? EXPLORING ENVIRONMENTAL, HEALTH, AND TECHNOLOGICAL PROBLEM SOLVING (1999), M. GRANGER MORGAN & MAX HENRION, UNCERTAINTY: A GUIDE TO DEALING WITH UNCERTAINTY IN QUANTITATIVE RISK AND POLICY ANALYSIS (1990).

<sup>&</sup>lt;sup>26</sup> A recent popular book hammers home the point that serious mistakes can follow from attending only to the average rather than the full probability distribution. *See* SAM L. SAVAGE, THE FLAW OF AVERAGES: WHY WE UNDERESTIMATE RISK IN THE FACE OF UNCERTAINTY (2009). One of Savage's examples, climate change, is particularly relevant for our purposes. Savage asks the reader to consider a hypothetical in which, on average, we expect no sea level rise — perhaps because our best estimate is that climate change won't happen. *Id.* at 291. However, assume further that we are not certain of this outcome, and the range of possible sea levels forms a bell curve. *Id.* 

Savage then observes that: "If the sea level ends up below expectations, then damage will be a bit lower than expected, but if sea level is above expectations, damage will be much worse than expected." *Id.* at 291-293. "Hence," he continues, "the damage associated with the average or expected sea level change may be tolerable, but averaged over all the things a scorned and furious Mother Nature might do to us, the

should not consider merely the "typical" California earthquake or the "typical" Gulf Coast hurricane. (Indeed, in those settings, the term "typical" may actually be misleading, as we will see.) This difficulty turns out to be critically important, as we will see later.

2. Risk analysis's blind spot. Risk analysis requires that risks be quantified. Not all risks can be readily quantified, and a focus on conventional risk analysis can lead to disregard of non-quantifiable risks. This can bias decision-making and mislead the public about the possible consequences. A policy of ignoring all unquantifiable harms is literally a recipe for disaster – consider the chance of a hijacked airplane being crashed into a building pre-2001 or the chance of a market meltdown pre-2009. Neither risk was quantifiable, and ignoring the risks led to catastrophic outcomes.

The Nuclear Regulatory Commission (NRC) has been a prime offender in ignoring uncertainties to reach desired results. Apparently in the belief that a problem is not significant unless it can be precisely quantified, the NRC refuses to discuss the possibility of terrorist attacks on nuclear facilities in its environmental impact statements because the risk cannot be quantified. As the Ninth Circuit explained in rejecting the NRC's policy, this position is indefensible under the relevant statute, the National Environmental Policy Act (NEPA): "If the risk of a terrorist attack is not insignificant, then NEPA obligates the NRC to take a "hard look" at the environmental consequences of that risk."<sup>27</sup> The court added that the "NRC's actions in other contexts reveal that the agency does not view the risk of terrorist attacks to be insignificant" and "[p]recise quantification is therefore beside the point."<sup>28</sup>

The Ninth Circuit seems clearly correct that the inability to quantify a risk does not justify failure to discuss it if there are other grounds for considering it significant. Yet, notwithstanding the force of the Ninth Circuit's reasoning, the NRC has adamantly refused to change its policy.<sup>29</sup> The NRC's policy has the effect of dismissing uncertainty from discussion and limiting consideration to quantifiable risks.

Similarly, the NRC had earlier attempted to ignore the uncertainties surrounding nuclear waste disposal. In November 1972, the government began a rulemaking

<sup>27</sup> San Luis Obispo Mothers for Peace v. Nuclear Regulatory Comm'n, 449 F.3d 1016, 1032 (9<sup>th</sup> Cir. 2006).

<sup>28</sup> Id.

damage could be disastrous." *Id.* at 293. Savage emphasizes that, "for this analysis I assumed that the expected temperature would be the same. Yet the uncertainty *alone* created great risk." *Id.* at 294. This argument is presented in more rigorous form in Part IV.

<sup>&</sup>lt;sup>29</sup>In re Amergen Energy Company, 2007 WL 595084, 50-0219-LR (Feb. 27 2007). Early, the agency had said that addressing terrorism was inappropriate because an EIS should only address environmental impacts that will result "with a fair degree of likelihood." *In re* Private Fuel Storage, L.L.C., 56 N.R.C. 350 (N.R.C. 2002). The agency's position was upheld in New Jersey Dep't of Envtl. Prot. v. United States Nuclear Regulatory Comm'n, 561 F.3d 132 (3d Cir. 2009), largely on the ground that relicensing of a plant would not be the "proximate cause" of any harm later resulting from a terrorist attack on the facility. *Id.* at 140. Legal readers will recall from the first year of law school that proximate cause is a slippery concept.

proceeding about the environmental costs associated with the uranium fuel cycle, including waste disposal.<sup>30</sup> The government decided to *assume* that the waste disposal problem would eventually be solved completely, an approach that ignores all potential uncertainties by the simple expedient of ignoring them. After years of agency consideration and litigation, the agency promulgated a rule that "explicitly stated that solidified high-level and transuranic wastes would remain buried in a federal repository and therefore would have no effect on the environment."<sup>31</sup> After further modifications, the agency "continued to adhere to the zero-release assumption that the solidified waste would not escape and harm the environment once the repository was sealed," despite acknowledging that "this assumption was uncertain because of the remote possibility that water might enter the repository, dissolve the radioactive materials, and transport them to the biosphere."<sup>32</sup> Unfazed by this lack of certainty, the NRC still "predicted" that the repository would remain intact and found "tentative but favorable" evidence that an appropriate site would be found.<sup>33</sup> In short, because the probability of a release was not known and the agency felt optimistic, it decided to simply ignore the problem. As we will see later, the risk of water transport of the materials turned out to be far from a remote possibility, and it remains to be seen whether the agency will ever be able to open a bedded-salt repository at any site.<sup>34</sup>

Remarkably, the Supreme Court upheld the NRC's decision to bury its head in the stand and ignore the waste disposal problem. Justice O'Connor's opinion for the Court emphasized three factors, none of which provide a justification for saying that a risk is precisely zero when the agency admits it does not know so. First, the zero assumption was made only for the limited purpose of ruling that waste disposal concerns would never be enough to tip the balance against licensing a particular plant.<sup>35</sup> Perhaps ignoring a small risk when only a single plant is at stake seemed reasonable. Yet, in doing so, the Court countenanced the agency ignoring the risk every time it approved a new plant. Since licensing is by its nature directed at individual plants, the implication is that waste disposal would never be considered in expanding the number of reactors.

Second, the Court said, the overall table of risks published by the agency was intended to be conservative, with the unduly low zero-risk assumption balanced by other

<sup>31</sup> *Id*.

<sup>32</sup> Id.

<sup>35</sup> *Id.* at 102.

<sup>&</sup>lt;sup>30</sup> Vermont Yankee Nuclear Power Corp. v. NRDC, 435 U.S. 519, 528 (1978).

<sup>&</sup>lt;sup>33</sup> *Id.* at 94 (emphasis added). "The Commission ultimately determined that any undue optimism in the assumption of appropriate selection and perfect performance of the repository is offset by the cautious assumption, reflected in other parts of the Table, that all radioactive gases in the spent fuel would escape during the initial 6 to 20 year period that the repository remained open, and thus did not significantly reduce the overall conservatism of the S-3 Table." *Id.* 

<sup>&</sup>lt;sup>34</sup> See infra text accompanying notes 245 to 247.

figures in the table<sup>36</sup> -- although how the Commission could know that the risks balanced, without knowing their magnitudes, is more than a bit unclear. The agency might just as well have said that it had a good feeling about the situation and left the discussion at that.

Third, "a reviewing court must remember that the Commission is making predictions, within its area of special expertise, at the frontiers of science. When examining this kind of scientific determination, as opposed to simple findings of fact, a reviewing court must generally be at its most deferential."<sup>37</sup> This is a wise general observation, but does it really apply when an agency acknowledges uncertainties about harm but arbitrarily decides to tell the public that the risk is zero? It might be appropriate for the agency to proceed despite the possible hazard, but it seems more doubtful that the agency should be able to affirmatively deny the very existence of a hazard when it admits that it is uncertain of this fact.

The upshot was that the agency was allowed to tell the public that possibility of a important problem was zero and to conduct its own affairs on that basis, despite knowing full well that the correctness of this position was uncertain.<sup>38</sup> Since the uncertainty was inconvenient for an agency that was determined to continue licensing nuclear power plants regardless, it was swept under the rug.<sup>39</sup>

<sup>36</sup> *Id.* at 102-103.

<sup>37</sup> *Id.* at 103-104.

<sup>38</sup> Richard Stewart describes the current nuclear waste disposal scheme as bankrupt. Richard B. Stewart, U.S. Nuclear Waste Law and Policy: Fixing a Bankrupt System, 17 NYU ENV. L.J. 783 (2008). Another blistering critique of the program from a decade earlier can be found in James Flynn et al., Redirecting the U.S. High-Level Nuclear Waste Program, 39 ENV. 6 (1997).

<sup>39</sup> Although the probability may have been nearly zero in the agency's preferred model of the world, we cannot dismiss the risk unless we also know that this particular model is almost certainly correct. For instance, suppose that there are two models available for the storage facility. NRC is eighty percent sure that Model A is correct, but thinks there is a twenty percent chance that Model B is correct. Model A predicts a zero probability of a release. Model B predicts a ten percent probability of a release. So the NRC's beliefs can be summarized as follows: "we think that there is an 80% chance that the way the world works is described by Model A and that there is consequently no risk of a release, but a 20% chance that the way the world works is described by Model B and that there is consequently a 10% chance of a release."

In this hypothetical situation, the NRC could truthfully say that the "best estimate of the probability of a release is zero," and that it is highly confident of that estimate. But taking both models into account, there is actually a twenty percent chance that Model B is right, and then a ten percent chance under Model B that a release would take place. Putting these together means that the probability of a release is ten percent of twenty percent  $(0.1 \times 0.2)$  or two percent (0.02). Two percent could be quite a significant risk if the costs associated with a release are high. No one would step on a commercial airplane with a two percent (one in fifty) chance of crashing. This example involves known probabilities rather than true uncertainty, but it illustrates a more general point: even if we are highly confident that the true probability of harm is zero, we are not justified in treating completely discounting the hazard, because if there is *any* possibility of a higher degree of harm, the expected level of harm is greater than zero. We can discount a hazard entirely only if we certain that it is zero. Since a probability cannot be less than zero, anything short of complete confidence in a zero level of risk means there is some possibility of harm.

Ignoring major problems because of uncertainty is an invitation to disaster. Indeed, as we will see, the NRC eventually ran into a wall. Almost forty years after the Court upheld its action, there is still no solution to the waste disposal problem in sight and the waste simply continues to pile up.<sup>40</sup> Given this history of ignoring uncertainty by fiat, the agency's credibility must be considered severely impaired.

In the context of nuclear waste, the Court countenanced an agency's decision to ignore uncertainty, but it did not affirmatively require the agency to do so. Presumably, the NRC could have treated the waste disposal problem as serious despite the lack of quantification, if it had chosen to do so. In the context of toxic chemical regulation, the Supreme Court has gone even further by barring the agency from acting unless it can quantify the probability of harm. Cancer threats to workers can only be addressed if the probabilities can be estimated well enough to survive judicial review.

The Court adopted this approach in *Industrial Union Department, AFL-CIO v. American Petroleum Institute* (better known as the *Benzene Case*),<sup>41</sup> holding that in order to justify regulation of a known carcinogen, the agency needed to quantify the risk and show that it surpassed a numerical threshold of significance. This holding has been criticized for requiring agencies to pretend to more confident quantification than the science really supports.<sup>42</sup> The upshot is that, even if very serious concerns exist about a chemical's safety in the workplace, industry has a free hand and can ignore the hazard completely until the agency can find some plausible basis for giving a numerical estimate of the risk.

The Supreme Court's preference for quantitative risk assessment may be understandable, but it is not always possible to obtain the necessary reliable estimates of probabilities. As we have seen in this section, risk assessment is a powerful

<sup>42</sup> See Howard A. Latin, The "Significance" of Toxic Health Risks: An Essay on Legal Decisionmaking Under Uncertainty, 10 ECOLOGY L.Q. 339 (1982). Prior to the Benzene case, courts were more willing to accept evidence of unquantified risks as sufficient. See John S. Applegate, The Story of Reserve Mining: Managing Scientific Uncertainty in Environmental Regulation, in RICHARD J. LAZARUS & OLIVER A. HOUCK, ENVIRONMENTAL LAW STORIES 70 (2005).

For example, in Lead Industries Association, Inc. v. Envtl. Protection Agency, 647 F.2d 1130 (D.C. Cir. 1980), the D.C. Circuit upheld a primary air quality standard for lead that incorporated an "adequate margin of safety." In setting the margin of safety, EPA had given no consideration to feasibility or cost. Moreover, the evidence of harm was unclear. Nevertheless, the court held that feasibility and cost were irrelevant and that EPA had acted properly in setting the margin of safety. The court explained that use of a margin of safety is an important method of protecting against effects that have not yet been uncovered by research and effects whose medical significance is a matter of disagreement.

<sup>&</sup>lt;sup>40</sup> See infra text accompanying notes 216 to 250.

<sup>&</sup>lt;sup>41</sup> 448 U.S. 607 (1980). The only applicable statutory provision dealing expressly with toxic chemicals in the workplace is section 6(b)(5) of the Occupational Health and Safety Act, 29 U.S.C. section 655(d)(5). This provision requires the agency to set a standard for any toxic material, "which most adequately assures, to the extent feasible, that no employee will suffer material impairment of health or functional capacity." Another section of the Act, section 3(8), 29 U.S.C. section 652(8), is also relevant. This section simply defines an occupational safety and health standard as a regulation setting any one of a variety of requirements "reasonably necessary or appropriate to provide safe or healthful places of employment."

methodology, but over-reliance can lead to a failure to acknowledge any risks that do not happen to lend themselves to the technique.

In the next section, we consider an alternative legal framework that relies less on quantification. Although the framework lacks the appealing rigor of risk assessment, it is more open to consideration of hazards that defy confident quantification.

# B. The Precautionary Principle

The European Union and other nations are less wedded to quantitative risk assessment than the United States. They are therefore more willing to take seriously hazards that cannot be quantified, via the precautionary principle. We will first discuss the principle and a partial analog found at one time in U.S. law, and then turn to debates about the validity of the precautionary principle.

*1. The principle.* In contrast to the U.S. reliance on conventional risk assessment, the European Union has favored an approach that more forthrightly addresses uncertainty: the precautionary principle. Indeed, the precautionary principle's influence is much broader than just the EU: "The precautionary principle is nothing short of ascendant on the international stage, so much so that many categorize it as constituting customary international law."<sup>43</sup>

The precautionary principle is endorsed in numerous international environmental statements and treaties. This principle has been explained on the basis of risk aversion or skepticism about the environment's ability to tolerate damage.<sup>44</sup> The precautionary principle now also appears as part of the Rio Declaration on international environmental law. Principle 15 of the Declaration states that "to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities," and that given "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."<sup>45</sup>

The precautionary principle also appears in international conventions on ozone, global climate and biodiversity.<sup>46</sup> It has also been adopted by Germany as a guide to environmental policy and has been invoked by courts in Canada, Pakistan, and India.<sup>47</sup>

<sup>&</sup>lt;sup>43</sup> Jonathan Remy Nash, *Standing and the Precautionary Principle*, 208 COLUM. L. REV. 494, 499 (2008).

<sup>&</sup>lt;sup>44</sup> See Daniel Farber, Eco-Pragmatism: Making Sensible Environmental Decisions in an Uncertain World 170 (1999).

<sup>&</sup>lt;sup>45</sup> 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)).

<sup>&</sup>lt;sup>46</sup> HUNTER, SALZMAN & ZELKE, *supra* note 45, at 410.

<sup>&</sup>lt;sup>47</sup> 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).

The precautionary principle served as the basis for the EU's effort to regulate the use of genetically modified organisms in foods.<sup>48</sup>

2. Worst-Case Scenarios in the U.S. The United States has not adopted the precautionary principle. Perhaps the closest the U.S. has come to the precautionary principle was an abortive requirement policymakers disclose worst-case scenarios. Dispute about worst-case scenarios arose in the context of environmental impact statements. 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.<sup>49</sup> Even a requirement that the agency take a hard look at the worst-case scenario, however, was too much for the American regulatory system to sustain, and the CEQ ended up repealing this requirement.

Still, at one time, White House guidance directed agencies to deal with catastrophic uncertainty by discussing the "worst-case" scenario.<sup>50</sup> A 1981 guidance document explained this rule as mandating "reasonable projections of the worst possible consequences of a proposed action."<sup>51</sup> The worst-case requirement was criticized as being excessively pessimistic and too intrusive on agency discretion.<sup>52</sup> CEQ issued a new regulation dealing with uncertainty, replacing the worst-case scenario requirement with a requirement that uncertainties be explicitly discussed.<sup>53</sup> The Supreme Court upheld this

40 C.F.R § 1502.22(b) (1991) [emphasis added].

<sup>51</sup> Vicki O. Masterman, Worst Case Analysis: The Final Chapter?, 19 ENVTL. L. REP. 10026, 10027 n.14 (1989).

<sup>52</sup> 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).

<sup>&</sup>lt;sup>48</sup> HUNTER, SALZMAN & ZELKE, *supra* note 45, at 407.

 <sup>&</sup>lt;sup>49</sup> See Robertson v. Methow Valley Citizens Council, 490 U.S. 332 (1989). For an overview, see Edward A. Fitzgerald, *The Rise and Fall of Worst Case Analysis*, 18 U. DAYTON L. REV. 1 (1992).

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 . . . 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.* 

<sup>&</sup>lt;sup>53</sup> 40 C.F.R. § 1502.22(b). The revised regulation applies when an agency completing an EIS has "incomplete information" that is relevant to "reasonably foreseeable significant adverse impacts," including "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." If this information is "essential to a reasoned choice among alternatives," and the cost of obtaining it is not "exorbitant," the information must be included.

If the information is relevant but cannot be obtained because the cost is too high or the "means to obtain it are not known," the impact statement must include four items: a statement of the information's unavailability; a statement of its relevance to reasonably foreseeable impacts; a summary of the existing scientific evidence relevant to assessing the impacts; and the agency's evaluation of these impacts based on

regulation in *Robertson v. Methow Valley Citizens Council* and held that NEPA does not require a worst-case analysis.<sup>54</sup>

As we will see later, the worst-case scenario is a relevant consideration – although not usually decisive -- in certain models of decision making under uncertainty.<sup>55</sup> This suggests that a reasonable decision maker or a member of the public assessing a project would desire this information. For that reason, the repeal of the "worst case scenario" regulation may have been misguided. Perhaps if agencies were instructed to explain both the worst-case and best-case scenarios, decision makers and the public would be better served. In any event, although the U.S. position may be something of an outlier internationally, the U.S. refusal to embrace the precautionary principle has support from a number of respected scholars, as shown in the next subsection.

3. The debate over the precautionary principle. Despite its broad international acceptance, the precautionary principle is controversial.<sup>56</sup> There seem to be three main criticisms. The first is its vagueness – or as one writer puts it, the principles "squishiness."<sup>57</sup> For instance, Christopher Stone found it "increasingly frustrating that there is no convergence as to what it means, or as to what regions of action (environment, public health) it is supposed to apply."<sup>58</sup> In some formulations, the precautionary principle is seemingly a mandate to halt activities when a sufficient level of risk appears, whereas in others it merely creates a presumption against activities potentially harmful to the environment, placing the burden of proof on the advocates of those activities.<sup>59</sup> But none of these formulations is precise, and Stone doubted whether any general rule can be formulated that is any more specific than "be careful!"<sup>60</sup> An admonition to exercise care is not necessarily undesirable, but it falls short of the guidance one would hope that the law would give decision makers.

The vagueness critique may be overstated, or at least the problem may be remediable. In response to such criticisms, a number of efforts have been made to sharpen the precautionary principle in three settings, (1) where "the heartland of the

<sup>60</sup> *Id.* at 10792.

generally accepted scientific methods. *Id.* This regulation seems quite reasonable, but it may not put enough pressure on agencies to face up to unpalatable adverse consequences from projects that they may well favor on other grounds.

<sup>&</sup>lt;sup>54</sup> Robertson v. Methow Valley Citizens Council, 490 U.S. 332 (1989).

<sup>&</sup>lt;sup>55</sup> See infa text accompanying notes 119 to 123.

<sup>&</sup>lt;sup>56</sup> For a recent update on the debate, see Fritz Allhoff, *Risk, Precaution, and Emerging Technologies*, 3 STUDIES IN ETHICS L. & TECH. (2009), *available at* <u>http://www.bepress.com/selt/vol3/iss2/art2</u>. Allhoff suggests that "precaution *supplements* cost-benefit analysis *given uncertainty*." *Id.* at 23 (emphasis in original).

<sup>&</sup>lt;sup>57</sup> Edward A. Parson, *The Big One: A Review of Richard Posner's Catastrophe: Risk and Response*, 45 J. ECON. LIT. 147, 152 (2007).

<sup>&</sup>lt;sup>58</sup> Christopher D. Stone, *Is There a Precautionary Principle?*, 31 ENVT. L. RPTR. 10790, 10791 (2001).

<sup>&</sup>lt;sup>59</sup> Id.

precautionary principle encompasses situations where the risk cannot be effectively assessed or reliably cabined, i.e., settings in which there is uncertainty rather than simply risk";<sup>61</sup> (2) where "a failure to regulate may result in irreversible harm," so that "an investment in regulation may be justified by a desire to retain flexibility by avoiding irreversible results";<sup>62</sup> or where harm would be catastrophic."<sup>63</sup> Although some advocates of the precautionary principle may not be attracted to the analytic tools advocated here, this Article can be considered a further effort along the lines of the first and third of these clarification strategies. The approaches discussed here focus on nonquantifiable risks (or at least, incompletely quantifiable ones) and are most appliacable in cases of catastrophic harm.

A second criticism of the precautionary principle is that government intervention creates risks of its own.<sup>64</sup> 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 explained, the precautionary principle might seem to call for stringent regulation of genetic engineering because of possible ecological risks, but the regulation itself would also create risks because "genetic engineering holds out a prospect of producing ecological and health benefits."<sup>65</sup> Thus, he says, "the precautionary principle would seem both to require and to forbid stringent regulation of genetic engineering."<sup>66</sup> Sunstein argues that 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."<sup>67</sup>

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 directives. For instance, application of the precautionary principle to nuclear power could lead to increased use of fossil fuels, accelerating global warming.

A third criticism connects the precautionary principle with defects in human cognition. Sunstein has argued that when the precautionary principle "seems to offer

<sup>67</sup> Id.

<sup>&</sup>lt;sup>61</sup> Nash, *supra* note 43, at 502-503.

<sup>&</sup>lt;sup>62</sup> Id.

<sup>&</sup>lt;sup>63</sup> Id.

<sup>&</sup>lt;sup>64</sup> 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).

<sup>&</sup>lt;sup>65</sup> Cass R. Sunstein, *Probability Neglect: Emotions, Worst Cases, and Law*, 11 YALE L.J. 61, 93 (2002). The version of precaution discussed in this article is more forgiving toward technologies with high upside potential and hence seems less vulnerable to this criticism.

<sup>&</sup>lt;sup>66</sup> Id.

guidance," it is "often because of the operation of probability neglect," meaning the cognitive incapacity of individuals to attend to the relevant risks.<sup>68</sup>

Considerable debate surrounds these criticisms. As we have seen, 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.<sup>69</sup> Alternatively, some supporters argue that the principle requires a kind of case-by-case, common law development.<sup>70</sup> The second criticism, regarding the existence of risks on both sides of regulatory decisions, may or may not always apply in practice. Regulations do not always create risks to health or the environment as a side effect. Often, they simply cost money. The third criticism, as it turns out, may be backwards: the precautionary principle may be 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 possible to find consensus on narrower ground. As subsection 4 shows, even Sunstein agrees that some special form of precaution is warranted for catastrophic risks.

4. Precautions against catastrophe. This Article focuses primarily on a specific form of uncertainty, that relating to possible catastrophic outcomes. As we have seen, Cass Sunstein is a long-time critic of the precautionary principle. He recognizes, however, that catastrophic risks may be different.<sup>72</sup> Sunstein proposes a number of different versions of the catastrophic risk precautionary principle, in increasing order of stringency. The first requires only that regulators take into account even highly unlikely catastrophes in determining expected utility.<sup>73</sup> A second dictates that regulators recall that social feedbacks may amplify the harm.<sup>74</sup> A third version "asks for a degree of risk aversion, on the theory that people do, and sometimes should, purchase insurance against

<sup>&</sup>lt;sup>68</sup> *Id.* at 94. Sunstein further elaborated his critique in Cass R. Sunstein, *Beyond the Precautionary Principle*, 151 U. PENN. L. REV. 1003 (2003).

<sup>&</sup>lt;sup>69</sup> 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 58.

<sup>&</sup>lt;sup>70</sup> See Stephen Toulmin, *The Case for Cosmic Prudence*, 56 TENN. L. REV. 29 (1998).

<sup>&</sup>lt;sup>71</sup> David A. Dana, *A Behavioral Economic Defense of the Precautionary Principle*, 97 NW. U. L. REV. 1315 (2003). Dana elaborates his position in David A. Dana, *The Contextual Rationality of the Precautionary Principle*, (2009), *available at* ssrn.com/abstract=1521802.

<sup>&</sup>lt;sup>72</sup> Cass R. Sunstein, *The Catastrophic Harm Precautionary Principle*, ISSUES IN LEGAL SCHOLARSHIP, CATASTROPHIC RISKS: PREVENTION, COMPENSATION, AND RECOVERY, 2007 *Article 3.*, http://www.bepress.com/ils/iss10/art3.

<sup>&</sup>lt;sup>73</sup> *Id.* at 28.

<sup>&</sup>lt;sup>74</sup> Id.

the worst kinds of harm."<sup>75</sup> Hence, he said, "a margin of safety is part of the Catastrophic Harm Precautionary Principle – with the degree of the margin depending on the costs of purchasing it."<sup>76</sup> Finally, Sunstein suggested, "it sometimes makes sense to adopt a still more aggressive form of the Catastrophic Harm Precautionary Principle, one that follows maximin by selecting the worst-case scenario and attempting to eliminate it."<sup>77</sup> (Maximin means selecting the strategy that has the *least bad* worst-case outcome – the decision maker "maximizes" the "minimum" utilities possible across the strategy space.) Sunstein added a caution, however that maximin is "not *generally* a sensible strategy in the environmental context or elsewhere" because it makes no sense when risks can actually be quantified even roughly and is not attractive when the worst-case scenario is only mildly bad or when the cure inflicts "serious losses of its own."<sup>78</sup>

Sunstein's observations point helpfully in the right direction, particularly regarding the special need for precaution regarding catastrophic risks and the possibility of using techniques that go beyond utility maximization. But identifying those techniques and clarifying their domain requires further work, and Sunstein does not attempt to apply his principle(s) to specific problems such as climate change. As we will see, current developments in economics and decision theory allow us to put some flesh on the concept of a catastrophic precautionary principle. Decision makers may ultimately need to rely on their own sense of the seriousness and plausibility of potential harms, but a great deal can be done to help structure the analysis and narrow the range of possible decisions.

This Article will identify analytic techniques that can be used to implement the catastrophic precautionary principle. Part III will provide theoretical underpinning for more rigorous analysis, and Part IV considers applications. The forms of precaution advocated in this article are more structured than conventional statements of the precautionary principle, allow both risks and benefits of decisions to be considered, and do not require that we discard risk assessment in situations where that technique is available. Thus, although implementing some of the same values as the precautionary principle, these new techniques are less vulnerable to attacks raised by critics.

#### **III. Understanding Catastrophic Uncertainty**

In trying to get increased analytic traction regarding catastrophic uncertainty, we will begin with a seemingly small modification of conventional risk analysis, but one with major consequences. Conventional risk analysis assumes, in effect, that feedback effects can safely be ignored, with the result that estimates of the probability of harm will be well-behaved. In this Part, we will see that feedback and other effects can result in

<sup>76</sup> Id.

<sup>77</sup> Id.

<sup>&</sup>lt;sup>75</sup> Id.

<sup>&</sup>lt;sup>78</sup> *Id.* at 28-29.

probability distributions that are much less tractable and pose much greater threats of extreme outcomes. We will also see that these models connect with an even more widespread situation in which we lack complete confidence in models and are therefore faced with unquantifiable uncertainties.

Section A shows how feedback effects can change the distribution of risks, creating an asymmetry between upside and downside outcomes. In particular, feedback effects may accentuate the likelihood of extreme outcomes. This phenomenon is the subject of popular phrases like "snowballing out of control" and "vicious cycle." Both phrases indicate that once a problem can begin, it can trigger a cycle of amplification that makes it worse and worse.

As Section B shows, some important regulatory problems seem to be associated with probability distributions in which extreme outcomes are more likely due to feedback effects, as compared with standard probability distributions. It also turns out to be very difficult if not impossible to pin down the exact probability of these extreme outcomes. Thus, despite the availability of extensive quantified information, we may find that the data cannot provide enough specificity to drive the final decision.

This observation leads us to Section C, which explains efforts by mathematicians and economic theorists to analyze situations in which multiple models of reality are plausible and quantification may be infeasible. These forms of analysis provide a more rigorous framework for addressing situations of deep uncertainty, although they do not eliminate the need for important judgments to be made by the decision maker.

# A. Feedback Effects and Extreme Outcomes

In many situations, most cases fall near the average, upside deviations are roughly as likely as downside deviations, and extreme deviations are extremely unlikely. These situations are relatively tractable in policy terms, but some policy issues require much more attention to potential extreme outcomes. This section will explain some of the dynamics behind these less tractable issues.

One way of understanding the problem begins with the concept of feedback effects.<sup>79</sup> The amplification or "gain" of a system with feedback can be characterized as the input times 1/(1 - f), where *f* is a measure of the strength of the feedback. Thus, g(f) = 1/(1-f), where g(f) represents the amount of gain for any given level of feedback.<sup>80</sup> The

<sup>&</sup>lt;sup>79</sup> Jainguao Liu et al., Complexity of Coupled Human and Natural Systems, 317 Sci. 1513 (2007).

<sup>&</sup>lt;sup>80</sup> Consider, for instance, a simple two-component system with a microphone and a loudspeaker. The microphone reduces the strength of the signal by a factor of *m*, the loudspeaker amplifies the sounds, then sends it back across the room to the microphone with its strength reduced by a factor of *l*. Let  $f = l^*m$ . Thus, each time the circuit is completed, the original signal is multiplied by f; it then goes through the circuit again where it comes out with strength  $f^2$ , etc. If this cycle is (nearly) instantaneous, the total amplification is  $1 + f + f^2 + f^3 + f^4 \dots = 1/(1-f)$  (by the algebra rule for summing geometric series). Lags in the process would complicate the results. Note that this formula applies only for f < 1; if f = 1 or f > 1, the series diverges (or in simpler terms, the sum is infinite).

output of the system is simply g(f) times the input, so g(f) measures the amplification due to feedback effects – like turning up a dial on a sound system.

One thing to note about this g(f) function is that it is sharply asymmetrical. Suppose, for example, that we think it is equally likely that f=1/4 and f=3/4. In other words, our best estimate is f=1/2, but with an uncertainty of  $\frac{1}{4}$  on either side. If we were sure that f was  $\frac{1}{2}$ , the "gain" from feedback effects would be  $1/(1 - \frac{1}{2}) = 2$ . Given the uncertainty, we know that the gain is either  $1/(1 - \frac{1}{4}) = 4/3 = 1.33$ , or  $1/(1 - \frac{3}{4}) = 4$ . So the range of outcomes is very wide.

Notice that if f is actually lower than our best estimate of 1/2, the effect is rather modest. But if f is higher, the effect is dramatic. In other words, uncertainty regarding the feedback parameter f is really bad news when the feedback involves undesirable outcomes: the best-case scenario offers little solace compared with the most likely outcome, but the worst-case scenario is dramatically worse than the most likely outcome.<sup>81</sup> This asymmetry follows from the fact that the graph of 1/(1-f) is asymmetrical on the interval from 0 (where the value of the function is 1) to 1 (where the value of the function is infinite).

For those whose taste does not run to equations or numerical examples, consider the familiar example of the feedback between a microphone and loud speakers. If the system is already experiencing a bit of feedback, turning the amplification slightly downward provides only modest benefits, while turning it slightly upward can result in an unnerving shriek from the speakers. Thus, uncertainty about the exact amount of feedback is mostly significant because of the risk that feedback will be higher than expected, resulting in much more noise, rather than the possibility that the feedback will be lower and the noise will be a bit more subdued. The implication is that uncertainty is greatest where it matters most, in terms of extreme events. The equation discussed above is merely a mathematical expression of this point.

The dispersion in outcomes is determined by the location of the midpoint estimate and the width of the interval of outcomes around that range. We can cut the range of outcomes in the previous example if we are able to narrow our estimates of f. For example, suppose that in the above example, we were able to cut the range of uncertainty to  $\frac{1}{4}$  -- that is, we know that f is either  $\frac{3}{8}$  or  $\frac{5}{8}$ . The range of outcomes becomes 1.8 (8/5) to 2.66 (8/3). This is real progress – we have cut the width of the range – but even so, the width remains uncomfortably large.

This rough numerical analysis actually underestimates the problem of improving the accuracy of predictions. The example assumes that the upward tail of the distribution of f has a strict cutoff well below 1.0 (3/4 in one example and 5/8 in the other). It also

<sup>&</sup>lt;sup>81</sup>This result is explained in Margaret S. Torn & John Harte, *Missing Feedbacks, Asymmetric Uncertainties, and the Underestimation of Future Warming*, 33 GEOPHYSICAL RES. LETTERS L10703 (2006).

uses a relatively small "best estimate" of one-half for f.<sup>82</sup> If we assumed instead that f has a probability distribution with a tail upwards toward 1 or that f itself is closer to 1, the 1/(1-f) formula would magnify the effect of the f-tail on estimates of the outcome of the system. This makes it all the more difficult to narrow uncertainties about the nature of the system by reducing uncertainties about f.<sup>83</sup> If individuals are risk averse, the uncertainties are also magnified again as differences in outcome are turned into differences in utility.

Thus, in systems where feedback is known to be substantial and potentially large, but is not exactly known, "fat tails" can emerge whose exact degree of "obesity" is hard to estimate accurately – and this in turn means that we will have difficult in estimating the probability of catastrophic outcomes. This exploration of feedback effects and extreme outcomes can be given a more rigorous foundation, as we will see in the next subsection.

# B. Fat-Tailed Distributions and Catastrophic Outcomes

There are good reasons to suspect that some important characteristics of real systems have what a statistician call "fat tails," making extreme events much more likely than one would expect from a bell curve.<sup>84</sup> 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.

*1. Introduction to fat tailed distributions.* When probabilities form a bell curve ("normal distribution"), most events are bunched near the average and extreme outcomes fade away quickly.<sup>85</sup> If the average cat weighs ten pounds, we can expect that most cats will be within a few pounds of the average, so a vet buying a scale could safely disregard the possibility of a two hundred pound Siamese. The term "fat tails" is used to describe systems that have a higher likelihood than the normal curve of extreme outcomes – in a graph, the tail of the distribution does not thin out as quickly as the normal distribution.<sup>86</sup>

<sup>&</sup>lt;sup>82</sup> To see why the magnitude of our best estimate of f matters, consider the results of using a best estimate of  $\frac{3}{4}$  rather than  $\frac{1}{2}$  for f. Then if the range of uncertainty for f is  $\frac{5}{8}$  to  $\frac{7}{8}$ , the range of uncertainty in outcomes is  $\frac{8}{3}$  to  $\frac{8}{1}$ , or 2.66 to 8.0. The uncertainty range in f of  $\frac{1}{4}$  turns into an uncertainty range in outcomes of 5.33. Note that using the same uncertainty in f but with a best estimate of  $\frac{1}{2}$ , as in the text, leads to an uncertainty in outcome of .86. So merely by shifting the best estimate of fwhile leaving the uncertainty of the estimate of f unchanged, we have amplified the increase in the uncertainty of the outcome by a factor of six.

<sup>&</sup>lt;sup>83</sup> See Gerard H. Roe and Marcia B. Baker, *Why is Climate Sensitivity So Unpredictable?*, 318 Sci. 629 (2006).

<sup>&</sup>lt;sup>84</sup> See infra text accompanying notes 90 to 93.

<sup>&</sup>lt;sup>85</sup> This can be seen from the graphs in Eric W. Weisstein, "Normal Distribution," <u>http://mathworld.wolfram.com/NormalDistribution.html</u> (last visited Jan. 24, 2010), which also reviews the mathematics of the normal distribution.

<sup>&</sup>lt;sup>86</sup> The term "fat tails" has recently come into vogue. According to one language expert: "If you want to make an impression at a board meeting or a Congressional hearing these bearish days, make a

A common version of fat tails is found in the statistical distribution called a "power law."<sup>87</sup> Indeed, a power law probability distribution makes it somewhat misleading to even talk about "typical" outcomes. Rather than following the familiar bell-curve distribution, complex systems often at least approximately follow power law distribution<sup>88</sup> in which the probability of an event is given by its magnitude taken to a fixed negative exponent.<sup>89</sup> A classic example is provided by earthquake magnitude. There are many more small earthquakes than large ones, and the pattern of decay in frequency fits a power law distribution.<sup>90</sup> Other examples include the size of extinction events, the number of species present in a habitat, and the size of the n<sup>th</sup> smallest species in a region,<sup>91</sup> clustering of desert vegetation,<sup>92</sup> and the size of gaps in rainforests.<sup>93</sup>

CONTEMP. PHYSICS 323-351 (Oct. 2005).

Two other commonly encountered fat-tailed distributions are the Cauchy distribution and the Levy distribution. These distributions behave like power law distributions in their tails but have different properties for smaller values. The Cauchy distribution, also called the Lorentz distribution, is a continuous distribution describing resonance behavior. It is symmetric and bell shaped, just like the normal distribution. It is a classical example of a distribution that has no mean (and consequently no variance). As a consequence the 'Law of Large Numbers' – which holds that if a trial is reproduced a large number of times *n*, then it becomes exceedingly improbable that the average of the outcomes of these *n* trials will differ significantly from the expected value of one outcome as *n* grows without limit -- does not apply. The Cauchy distribution is just the original Cauchy distribution (sample size 1). So the distribution of the sample size. This distribution is just the original Cauchy distribution (sample size 1). So the distribution of the sample mean does not "shrink down" as the sample size increases. *See* Eric M. Weisstein, "Cauchy Distribution," *available at* <u>http://mathworld.wolfram.com/CauchyDistribution.html</u> (last visited Jan. 24, 2010). For a discussion of the Levy distribution, a more advanced treatment is found in SVETLOZAR T. RACHEV, CHRISTIAN MENN, AND FRANK J. FABOZZI, FAT-TAILED AND SKEWED ASSET RETURN DISTRIBUTIONS: IMPLICATIONS FOR RISK MANAGEMENT, PORTFOLIO SELECTION, AND OPTION PRICING 2, 81-118 (2005).

<sup>88</sup> It can be difficult to distinguish power laws from other fat-tailed distributions empirically. *See* Aaron Clauset, Cosma Rohilla Shalizi, and M.E. J. Newman, *Power-Law Distributions in Empirical Data* (Feb. 2, 2009), *available at* http://arxiv.org/abs/0706.1062.

<sup>89</sup> See Richard Sole & Brian Goodwin, Signs of Life: How Complexity Pervades Biology 201 (2000).

<sup>90</sup> SIMON LEVIN, FRAGILE DOMINION: COMPLEXITY AND THE COMMONS (1999).

<sup>91</sup> See SOLE & GOODWIN, supra note 89, at 201.

<sup>92</sup> Todd M. Scanalon, et al., *Positive Feedbacks Promote Power-Law Clustering of Kalahari Vegetation*, 449 NATURE 209 (2007).

<sup>93</sup> *Id.* at 205. For another example of power laws in ecology, see Levin, *supra* note 90, at 55. For a compilation of examples of power laws in many different contexts, see M.E. J. Newman, *Power Laws, Pareto Distributions and Zipf's Law*, 46 CONTEMPORARY PHYSICS 323 (2005).

hurumphing news and employ the figure of speech now sweeping the economic world: 'But what about the *fat tail*?'" William Safire, *Fat Tail*, N.Y. TIMES MAGAZINE, February 5, 2009.

<sup>&</sup>lt;sup>87</sup> For an introduction to power laws, see MANFRED SCHROEDER, FRACTALS, CHAOS, POWER LAWS: MINUTES FROM AN INFINITE PARADISE 103-19 (1991). For a discussion of processes that generate power laws, see Michael Mitzenmacher, *A Brief History of Generative Models for Power Law and Lognormal Distributions*, 1 INTERNET MATHEMATICS 226, available at http://scholar.google.com/scholar?hl=en&lr=&q=related:2djp9QDvm8MJ:scholar.google.com/&um=1&ie =UTF-8&ei=CbFDS77ZOpPQsQPojc28BA&sa=X&oi=science\_links&resnum=1&ct=slrelated&ved=0CAkQzwIwAA; M.E.J. Newman, *Power Laws, Pareto Distributions and Zipf's Law*, 46

Contrasting power laws with the normal curve governing characteristics such as human heights, a physicist who studies complex networks points out that 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." <sup>94</sup> Thus, "the distinguishing feature of a power law is not only that there are many small events but that the numerous tiny events coexist with a few very large ones."<sup>95</sup>

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."<sup>96</sup> Power laws conflict with our usual view of the world as consisting of routine outcomes accompanied by small random fluctuations.

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 task has already taken five days, we might expect it to be wrapped up quickly since we are already past the expected due date. (If we know a person is at least six feet tall, the best guess is that the height is only a little more, not that it is eight feet.) But in fact, the expected time to completion may now be fifteen days. <sup>97</sup> The reason is that the curve flattens out much less quickly as we move farther out. As the task 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. Similarly, with a fat tailed distribution, if we know that the harm from some event will be *at least* \$5 billion, the best estimate could be that it will be much higher – say \$15 billion.<sup>98</sup>

This paradoxical behavior is characteristic of fat tailed distribution. Financial managers use the mean excess – in this case, the fifteen-day expected time to completion given that the job has taken five days – to identify fat tailed distributions. This excess time is limited for thin tailed distributions, but "fat tails push this excess ever upward."<sup>99</sup>

Because of this attribute of fat tail distributions, it can be misleading to cut off the curve at some benchmark probability level. For example, suppose that we were to decide

<sup>&</sup>lt;sup>94</sup> Albert-Laszlo Barabasi, Linked: The New Science of Networks 67-68 (2002).

<sup>&</sup>lt;sup>95</sup> Id.

<sup>&</sup>lt;sup>96</sup> *Id.* at 68 n.1.

<sup>&</sup>lt;sup>97</sup> This example is given in SCHROEDER, *supra* note 87, at 157.

<sup>&</sup>lt;sup>98</sup> For a more technical discussion of this phenomenon, see Karl Sigman, *Appendix: A Primer on Heavy-Tailed Distributions*, 33 QUEING SYSTEMS 261 (1999).

<sup>&</sup>lt;sup>99</sup> Carolyn Kousky & Roger M. Cooke, *Climate Change and Risk Management: Challenges for Insurance, Adaptation, and Loss Estimation* (RFF Discussion Paper March 2009), *available at* <u>http://ssrn.com/abstract=1346387</u>.

that any risk below one in ten thousand is not worth considering in some situation. There might be a one in ten thousand risk of an event causing a harm of \$1 billion dollars. But viewing this figure as encapsulating the downside risk would be misleading – for if we know that the harm is at least that size, the expected harm might well be a substantial multiple of the \$1 billion figure. To determine the downside risk, we need to consider the whole tail of the distribution past 1/10,000, rather than using the amount of harm associated with a 1/10,000 risk as our estimate.

A power law (like some other fat-tailed distributions) can have an infinite variance or even an infinite expected value.<sup>100</sup> (Recall that the expected value is the probability of an event times its value. Variance is a measure of the degree of economic riskiness of the outcome.) The chances of a large event may decrease rapidly but not rapidly enough to make up for the increasing magnitude of the event.<sup>101</sup> If we were talking about an uncertain environmental harm, this could mean that either the expected value of the harm might be infinite, or the expected value might be finite but the variance might be infinite, so that in some sense the expected value is associated with indefinitely large risks. Infinitely bad outcomes are impossible in a literal sense because there are physical limits to how much harm can occur, but even if the infinities are not literal, they suggest the existence of extraordinary downside risks.

2. The uncertainty surrounding tail thickness. The existence of fat tails clearly has relevance to policy, but we do not have "a commonly accepted usable economic framework for dealing with these kinds of thick-tailed extreme disasters" – partly because these "probability distributions are inherently difficult to estimate."<sup>102</sup> The reason that the probabilities are difficult to estimate is that data will rarely include instances from the tail (because the events are rare), making it impossible to estimate just how quickly the tail tapers off. In other words, fat tails bring with them an epistemic problem.

Martin Weitzman has shown on the basis of very general considerations of statistical and economic theory that it often "is difficult to infer (or even to model accurately) the probabilities of events far outside the usual range of experience" and that this ultimately leads to a fat-tailed probability distribution of utility losses.<sup>103</sup> Weitzman also shows that even if the "true" probability distribution has a thin tail, the decision-

<sup>&</sup>lt;sup>100</sup> See Benoit B. Mandelbrot, The Fractal Geometry of Nature 337-38 (1983).

<sup>&</sup>lt;sup>101</sup> For example, consider x varying from zero to infinity, with  $p(x) = (1 + x)^{-2}$ . Because of their risk characteristics, fat tails can pose serious problems to insuring risks, see Roger M. Cooke and Carolyn Kousky, *Are Catastrophers Insurable*?, 172 RESOURCES 18, 20 (Summer 2009).

<sup>&</sup>lt;sup>102</sup> Martin Weitzman, *The Stern Review on the Economics of Climate Change*, 45 J. ECON. LITERATURE 703, 717 (2007).

<sup>&</sup>lt;sup>103</sup> *Id.* at 3 n.4. Indeed, even determining that data exhibits a fat-tailed distribution such as a power law rather than a thinner-tailed distribution such as the lognormal distribution can be difficult. See Newman, supra note xx, at 329-330. The differences can be quite subtle: the same basic model can lead to a power law or a lognormal distribution, depending on whether there is a boundary at an extreme (for example, a requirement that outcomes cannot go below zero). See Michael Mitzenmacher, *A Brief History of Generative Models for Power Law and Lognormal Distributions*, 1 Internet Mathematics 226-251.

maker may still be faced with a fat tailed distribution as a practical matter because it is impossible to get enough evidence to estimate the tail with precision. (We might assume that losses cannot be infinite and truncate the tail on that basis – but this involves an additional source of uncertainty since we are not sure of exactly where to truncate the tail.) In effect, estimation errors fatten up the tail. If the parameters of the true distribution are not known with certainty, taking that second-level uncertainty into account leads decision-makers to act as if they were facing a fat-tailed distribution. These fat tails "represent structural or deep uncertainty about the possibility of rare high-impact disasters that . . . 'scare' any [risk-averse] agent.<sup>104</sup>

Thus, an inability to precisely estimate the parameters of a thin-tailed distribution – a form of second-order uncertainty about the first-order probability distribution – may confront the decision maker with a fat tailed distribution in practical terms. Yet we lack good analytic techniques for quantifying total risk when the distribution has a fat tail.<sup>105</sup>Thus, fat tailed distributions and uncertainty seem to be connected at a deep level.

For these reasons, consideration of fat tails leads naturally to the question of what to do in the absence of an ability to quantify risks in a satisfactory way.<sup>106</sup> There is no completely satisfactory answer to that question, but the next subsection shows that some significant advances have been made in addressing unquantifiable risks.

# B. Uncertainty Models and Worst Case Scenarios

As Weitzman has observed in the context of climate change, what is truly unsettling for an application of expected utility theory "are the unknowns: deep structural uncertainty in the science coupled with an economic inability to evaluate meaningfully the catastrophic losses from disastrous temperature changes."<sup>107</sup> There are several approaches to analyzing such situations, which we will consider in this section.

<sup>&</sup>lt;sup>104</sup> Martin L. Weitzman, On Modeling and Interpreting the Economics of Catastrophic Climate Change, 91 REV. OF ECON. AND STATISTICS 1, 9 (2009). The distribution that he derives is not a power law but another fat-tailed distribution known for historical reasons as the "student-t." *Id.* at 8. This distribution looks like a bell curve "except that the probabilities are somewhat more stretched out, making the tails appear relatively fatter at the expense of a slightly thinner center." *Id.* at 8.

<sup>&</sup>lt;sup>105</sup> One emerging possibility is the use of "real options" analysis, which has only recently been applied to fat tailed situations such as climate change. *See* Jon Anda, Alexander Golub, and Elena Strukova, *Economics of Climate Change Under Uncertainty: Benefits of Flexibility*, 37 ENERGY POLICY 1345 (2009) (concluding that benefits of early mitigation are increased by uncertainties that could be resolved later).

<sup>&</sup>lt;sup>106</sup> Under some circumstances, we have the advantage of having some information about a distribution, and the question then is how to best select the type of distribution. A technique called "maximum entropy" (MaxEnt) can be helpful in making this choice. MaxEnt selects the distribution that, in a sense derived from information theory, avoids the use of any additional assumptions about the shape of the distribution apart from the given information. In other words, MaxEnt selects the distribution that is as "smooth and flat as possible" to be the least-biased inference about the distribution. *See J. Harte, T. Zillo, E. Conslisk, & A.B. Smith, Maximum Entropy and the State-Variable Approach to Macroecology*, 89 ECOLOGY 2700, 2701 (2008).

<sup>&</sup>lt;sup>107</sup> Weitzman, *supra* note 104, at 1.

*1. Models of uncertainty and ambiguity aversion.* "Ambiguity" refers to situations where the true probability distribution of outcomes is not known.<sup>108</sup> There is strong empirical evidence that people are averse to ambiguity. The classic experiment involves a choice between two urns. One is known to contain half red balls and half blue; the other contains both colors but in unknown proportions. Regardless of which color they are asked to bet on, most individuals prefer to place their bet on the urn with the known composition.<sup>109</sup> This is inconsistent with standard theories of rational decision making: if the experimental subjects prefer the known urn when asked to bet on red, that implies that they think that there are fewer than fifty percent red balls in the other urn. Consequently, they should prefer the second urn when asked to bet on blue – if it is less than half red it must be more than half blue -- but they do not.<sup>110</sup> Apparently, people prefer not to bet on an urn whose composition is uncertain.<sup>111</sup> Such aversion to

<sup>110</sup> One might think that this behavior could be explained by first assuming that the subjects actually attribute the equal numerical probability to each of the possible scenarios and then invoking risk aversion. To see why this idea is incorrect, suppose that we knew that the "uncertain" urn is either all red or all blue, that the probability of the urn being red is p, and that p is equally likely to be anywhere between 0 and 1. On this assumption, the probability of drawing a red ball from the uncertain urn is:

 $P = P = \int_{0}^{1} p \cdot 1 dp = 1/2$ . (since 1 is the probability of a red ball if the urn is red and p is the

probability it is red). This is exactly the same as the probability from the half-red, half-blue urn, so there is no reason to favor one over the other. Another way of seeing this more directly is to assume that we have a choice between the following gambles:

(1) Betting that the next ball drawn from a half-red, half-blue urn will be red.

(2) Betting on a red ball being produced by the following scenario. First, we flip a coin. Second, if the coin come out heads, we draw a red ball from an all-red urn; if tails, from an all-blue urn.

Both of these are just two different mechanisms for producing a fifty-percent probability of red, so with or without risk aversion, a person should be indifferent between them. Thus, risk aversion cannot account for the Ellsberg paradox.

<sup>111</sup> Nicholar Barberis & Richard Thaler, *A Survey of Behavioral Finance, in* HANDBOOK OF THE ECONOMICS OF FINANCE 1074 (G.M. Constantinides, M. Harris & R. Stulz eds., 2003).

<sup>&</sup>lt;sup>108</sup> For other legal applications of ambiguity models, see Uzi Segal & Alex Stein, *Ambiguity Aversion* and the Criminal Process, 81 NOTRE DAME L. REV. 1495 (2006) (higher ambiguity aversion of defendants as opposed to prosecutors results in unbalanced plea negotiations); Eric Talley, *On Uncertainty, Ambiguity,* and Contractual Conditions, 34 DELAWARE J. OF CORP. LAW 755 (2009) (ambiguity explains why the possibility of adverse events sometimes results in use of a conditions clause rather than a price adjustment); Joshua C. Teitelbaum, *A Unilateral Accident Model under Ambiguity*, 36 J. LEGAL STUD. 431 (2007) (negligence rules may be superior to strict liability under conditions of ambiguity).

<sup>&</sup>lt;sup>109</sup> See Gideon Keren and Leonie E.M. Gerristen, On the Robustness and Possible Accounts of Ambiguity Aversion, 103 ACTA PSYCHOLOGICA 149 (1999) ("Ambiguity aversion is one of the most robust pheomena documented in the decision making literature . . . ") The researchers found in one experiment that "ambiguity avoidance is so pervasive that it extends even to situations in which the likelihood of winning in the ambiguity condition is higher than in the risky conditions." *Id.* at 157.

ambiguity "appears in a wide variety of contexts."<sup>112</sup> Ambiguity aversion may reflect a sense of lacking competence to evaluate a gamble.<sup>113</sup>

There are a number of different approaches to modeling ambiguity.<sup>114</sup> One is the Klibanoff-Marinacci-Mukerji model.<sup>115</sup> This approach assumes that decision-makers have several different possible probability distributions (pdfs) in front of them, and that they evaluate decisions based on a function  $\varphi$ . This function in turn is based on (a) the likelihood that the decision maker attaches to different pdfs, (b) the degree to which the decision maker is averse to taking chances about which pdf is right, and (c) the expected utility of a decision under each of the pdfs. In simpler terms, the  $\varphi$ -function combines the expected outcome under each pdf according to the decision maker's beliefs about the pdfs and attitude toward ambiguity. The shape of the  $\varphi$ -function determines in a straightforward way whether the decision maker is ambiguity averse, ambiguity neutral, or ambiguity seeking.<sup>116</sup>

The Klibanoff-Marinacci-Mukerji model has an appealing degree of generality (and is actually less formidable mathematically than some alternatives). But this model is not easily applied, since we need to know  $\varphi$  and the decision-maker needs to be able to attach numerical weights to the likelihood of specific pdfs, which may not be possible in cases of true uncertainty.<sup>117</sup>

Other models of ambiguity are more tractable. As economist Sir Nicholas Stern explains, in these models of uncertainty decision-maker, who is trying to choose which action to take, does not know which of several probability distributions is more or less likely for any given action.<sup>118</sup> He explains that it can be shown the decision maker

<sup>112</sup> *Id.* at 1075.

<sup>113</sup> *Id*.

<sup>115</sup> Peter Kilbanoff, Massimo Marinacci, & Sujoy Mukerji, *A Smooth Model of Decision Making under Ambiguity*, 73 ECONOMETRICA 1849 (2005).

<sup>116</sup> Id. at 1869-70.

<sup>117</sup> The model has been extended into dynamic choice situations where the decision maker receives additional information over time. *See* Peter Klibanoff, Massimo Marinacci, & Sujoy Mukerji, *Recursive Smooth Ambiguity Preferences*, 144 J. ECON. THEORY 930 (2008).

<sup>118</sup> STERN, *supra* note 2, at 39. For discussion of the so-called  $\alpha$ -maxmin model in the context of a more general theory, see Paolo Ghirardato, Fabio Maccheroni, & Massimo Marinacci, *Differentiating Ambiguity and Ambiguity Attitude*, 118 J. ECON. THEORY 133, 153-155 (2004) (the crucial result is proposition 19(ii) on page 154).  $\alpha$ -Maxmin can be derived from the assumption that decision makers are indifferent between acts which result in the same range of expected utilities over the set of scenarios. *See* Paolo Ghirardato, Fabio Maccheroni, and Massimo Marinacci, *Ambiguity from the Differential Viewpoint* Cal. Tech. Social Science Working Paper 1130, 6 (April 2002). If decision makers care only about the utility associated with outcomes, the assumption seems plausible if we assume that the decision maker has no ability or willingness to evaluate the likelihood of different scenarios, so outcomes across scenarios only reflect the range of possibilities.

<sup>&</sup>lt;sup>114</sup> A good summary can be found in Alessandro Vercelli, *Hard Uncertainty and Environmental Policy, in* SUSTAINABILITY: DYNAMICS AND UNCERTAINTY 191, 196-205 (Graciela Chichilnsky et al. eds., 1998).

"would act as if she chooses the action that maximizes a weighted average of the worst expected utility and the best expected utility . . . The weight place on the worst outcome would be influenced by concern about the magnitude of associated threats, or pessimism, and possibly any hunch about which probability might be more or less plausible."<sup>119</sup>

These models are sometimes called  $\alpha$ -maxmin models, with  $\alpha$  representing the weighting factor between best and worst cases.<sup>120</sup> One way to understand these models is that we might want to minimize our regret if we make the wrong decision, where we regret disastrous outcomes that lead to the worst-case scenario but we also regret having missed the opportunity to achieve the best-case scenario. Alternatively,  $\alpha$  can be a measure of the balance between our hopes (for the best case) and our fears (of the worst case).<sup>121</sup>

Applying these  $\alpha$ -maxmin models as a guide to action leads to what we might call the  $\alpha$ -precautionary principle. Unlike most formulations of the precautionary principle,  $\alpha$ -precaution is not only aimed at avoiding the worst-case scenario; it also involves precautions against losing the possible benefits of the best-case scenario.<sup>122</sup> In some situations discussed in this article, the best-case scenario is more or less neutral, so that  $\alpha$ precaution is not much different than pure loss avoidance unless the decision maker is very optimistic and uses an especially low  $\alpha$ . But where the best-case scenario is potentially extremely beneficial, unless the decision maker's  $\alpha$  is very high,  $\alpha$ -precaution will suggest a more neutral attitude toward uncertainty in order to take advantage of potential upside gains.

For example, suppose we have two models about what will happen if a certain decision is made. We assume that each one provides us enough information to allow the use of conventional risk assessment techniques *if* we were to assume that the model was correct. For instance, one model might have an expected harm of \$1 billion and a

<sup>&</sup>lt;sup>119</sup> Id.

<sup>&</sup>lt;sup>120</sup> A key point in applying these models is identifying the best and worst case scenarios. Use of the model might encourage interest groups to put forward exaggerated scenarios (although this is probably already an incentive for other reasons.)

<sup>&</sup>lt;sup>121</sup> Some economists and finance theorists postulate that risk measures should focus solely on adverse outcomes, a concept known as downside risk. *See* Michael Hanemann, et al., Climate Change Impacts of Urban and Agricultural Sectors in California 36-41 (Draft Report from the California Climate Change Center) (December 2008) (describing theories of downside risk) (on file with author). The magnitude of  $\alpha$  can be considered a measure, in the uncertainty context, of the weight placed on downside outcomes. A low  $\alpha$  indicates an aversion to "downside uncertainty."

<sup>&</sup>lt;sup>122</sup> If α=1, then α-maximin becomes ordinary maxmin, in which only the worst-case matters. For an axiomatic treatment of maxmin, see Itzhak Gilboa & David Schmeidler, *Maxmin Expected Utility With Non-Unique Prior*, 18 J. MATH. ECON. 141 (1988). The α parameter could be considered a measure of what Keynes called "animal spirits." *See* CLARKE, *supra* note 6, at 156. These models are somewhat akin to Dempster-Shafter models of decision making which use a weighted average of high and low extremes, although the weighting factor (ρ) represents a relative probability rather than ambiguity aversion. *See* Thomas M. Strat, *Decision Analysis Using Belief Functions*, in Ronald R. Yager, Januz Kacprzyk & Mario Fedrizzi, ADVANCES IN THE DEMPSTER-SHAFER THEORY OF EVIDENCE 285, 306 (1994).

variance of \$0.2 billion; the other an expected harm of \$10 billion and a variance of \$3 billion. If we know the degree of risk aversion of the decision-maker, we can translate each outcome into an expected utility figure for each model. The trouble is that we do not know which model is right, or even the probability of correctness. Hence, the situation is characterized by uncertainty. To assess the consequences associated with the decision, we then use a weighted average of these two figures based on our degree of pessimism and ambiguity aversion. This averaging between models allows us to compare the proposed course of action with other options.

Note that we could use this information in various ways: (1) to decide whether it is worth conducting further research in the hope of narrowing the range of uncertainty; (2) to decide whether to invest in methods to reduce feedback and hence "thin out" the fat tails and narrow ambiguity, or (3) simply to decide whether or not to undertake the action. The focus in this paper is on determining how we should assess outcomes when we are uncertain about the consequences of action or inaction, rather than on strategies that might be devised once the outcomes are assessed.

An interesting variant of  $\alpha$ -maxmin uses a weighted average that includes not only the best-case and worst-case scenarios but also the expected value of the betterunderstood, intermediate part of the probability distribution.<sup>123</sup> This approach "is a combination between the mathematical expectation of all the possible outcomes and the most extreme ones."<sup>124</sup> This tri-factor approach may be "suitable for useful implementations in situations that entangle both more reliable ('risky') consequences and less known ('uncertain'), extreme outcomes."<sup>125</sup> It requires a better understanding of the mid-range outcomes and their probabilities, however, than does alpha precaution.

 $\alpha$ -Maxmin has some important virtues in terms of process. Rather than asking the decision maker to assess highly technical probability distributions and modeling, it simply presents the decision maker with three questions to consider: "What is the best-case outcome that is plausible enough to be worth considering? What is the worst-case scenario that is worth considering? And how optimistic or pessimistic should we be in balancing these possibilities? These questions are simple enough for politicians and members of the public to understand. More importantly, rather than concealing values judgments in technical analysis by experts, they present the key value judgments directly to the elected or appointed officials who should be making them. Finally, these questions also lend themselves to oversight by higher-level executive officials, legislators, and the press.

<sup>&</sup>lt;sup>123</sup> See Marcello Asili, Alain Chateauneuf, & Fulvio Fontini, Precautionary Principle as a Rule of Choice With Optimism on Windfall Gains and Pessimism on Catastrophic Losses, 67 ECOLOGICAL ECON. 485 (2008).

<sup>&</sup>lt;sup>124</sup> *Id.* at 490.

<sup>&</sup>lt;sup>125</sup> *Id*.

3. Relating the models. We seem to be suffering from an embarrassment of riches, in the sense of having too many different models for decision making in situations where extreme outcomes weigh heavily. At present, it is not clear that any one model will emerge as the most useful for all situations. For that reason, the ambiguity models should be seen as providing decision makers with a collection of tools for clarifying their analysis rather than providing a clearly defined path to the "right" decision.

Among this group of tools, what I have been calling  $\alpha$ -precaution (utilizing  $\alpha$ -maxmin) has a number of attractive features. First, it is complex enough to allow the decision maker to continue both the upside and downside possibilities, without requiring detailed probability information that is unlikely to be available. Second, it is transparent. Although the math behind this decision tool is formidable, actually applying the tool requires only simple arithmetic. The user must decide on what parameter value for  $\alpha$  to use, but this choice is intuitively graspable as a measure of optimism versus pessimism.<sup>126</sup> Third,  $\alpha$ -maxmin can be useful in coordinating government policy. An oversight agency such as OMB can provide benchmark values of  $\alpha$  and rules for conducting sensitivity analysis. It can review departures from the benchmarks, where those are important, in order to determine that an agency's degree of pessimism or optimism about a problem are consistent with administration policy.

Models of uncertainty and fat tail models do not map precisely into each other although they both give us ways of thinking about catastrophic outcomes. Fat tail models are technically risk models rather than uncertainty models because the probability distribution is (somewhat) known. The mathematics in fat tailed models thus looks different from that used in ambiguity models. Although these models have not been formally linked, it is not hard to find a connection. The ambiguity models can be viewed as useful ways of approaching situations where in fact there is no worst-case scenario because the outcomes can be almost infinitely bad with some nonzero probability.

A heuristic interpretation links the difficulties of dealing with the dangers incorporated in fat-tail distributions with the somewhat severe nature of the ambiguity-aversion models. Rather than trying to solve the intractable problem of the potential infinities in fat tail distributions, we can cut off the tail at some plausible "worst case" – but then make up for our inability to directly bring the full spectrum of outcomes into account by giving heavy weight to the chosen bad scenario. (In essence, we are "overweighting" the chosen scenario to make up for excluding the further end of the tail.) In other words, the extremism of maxmin or weighted decisions could be seen as a way of incorporating the fact that we have shunted aside the full range of horrific outcomes. Ambiguity between a finite set of models then functions as a stand-in for the fact that there are multiple other possible models, perhaps only poorly understood, that could lead to much worse outcomes.

<sup>&</sup>lt;sup>126</sup> We might be able to narrow the range for  $\alpha$  through empirical evidence about how individuals approach decision making in situations characterized by ambiguity or through experience over time that might allow officials to develop norms about the appropriate  $\alpha$ .

Alternatively, we might focus on the uncertainties presented by fat tailed distributions themselves. In a situation where a fat-tailed distribution is a possibility, the decision may face several unknowns: whether the distribution actually does have a fat-tail, the type and parameters of the fat-tailed distribution, or whether (and where) to truncate the distribution if there is some possible upper bound on outcomes. Thus, even if a specific fat-tailed distribution (with or without truncation) actually does characterize the situation, the barriers to full knowledge of the distribution may mean that the decision maker's problem is more one of uncertainty than risk, making ambiguity models relevant.

*3. Locating robust solutions.* Another approach, which also finds its roots in consideration of worst-case scenarios, is to use scenario planning to identify unacceptable courses of action and then choose the most appealing remaining alternatives. Robustness rather than optimality is the goal. RAND researchers have developed a particularly promising method to use computer assistance in scenario planning.<sup>127</sup> RAND's Robust Decision Making (RDM) technique provides a systematic way of exploring large numbers of possible policies to identify robust solutions.<sup>128</sup>

During each stage of the analysis, RDM uses statistical analysis to identify policies that perform well over many possible situations. It then uses data mining techniques to identify the future conditions under which such policies fail. New policies are then designed to cope with those weaknesses, and the process is repeated for the revised set of policies. As the process continues, policies become robust under an increasing range of circumstances, and the remaining vulnerabilities are pinpointed for decision makers.<sup>129</sup> More specifically, "RDM uses computer models to estimate the performance of policies for individually quantified futures, where futures are distinguished by unique sets of plausible input parameter values."<sup>130</sup> Then, "RDM evaluates policy models once for each combination of candidate policy and plausible

<sup>129</sup>*Id.* at 132.

<sup>&</sup>lt;sup>127</sup> See David G. Groves, New Methods for Identifying Robust Long-term Water Resources Management Strategies for California 12 (RAND 2006), available at http://www.rand.org/pubs/rgs dissertations/2006/RAND RGSD196.pdf.

For an effort to test the usability of this approach for water agencies, see David G. Groves, et al., Presenting Uncertainty to Water-resource Managers: A Summary of Workshops with the Inland Empire Utilities Agency 74 (2008), available at www.rand.org/pubs/technical reports/2008/RAND TR505.appendixB.pdf.

<sup>&</sup>lt;sup>128</sup> This is a more formalized version of the familiar technique of scenario analysis. For a description of scenario analysis, see JAMES A. DEWAR, ASSUMPTION-BASED PLANNING: A TOOL FOR REDUCING AVOIDABLE SURPRISES 130–42 (2002).

<sup>&</sup>lt;sup>130</sup> *Id.* at 124–25 (describing how the method achieves "robust" policies that are "relatively insensitive to the key uncertainties and different preferences held by decision makers"). *See also* David G. Groves and Robert J. Lempert, *A New Analytic Method for Finding Policy-relevant Scenarios*, 17 GLOBAL ENV. CHANGE 73, 75 (2007) ("The central idea is to use multiple runs of computer simulation models to identify those scenarios most important to the choices facing decision makers," based on the foundation of RDM).

future state of the world to create large ensembles of futures."<sup>131</sup> The analysis may include a few hundred to hundreds of thousands of cases.<sup>132</sup>

A related concept, which discards strategies known to be dangerous, is known as the safe minimum standards (SMS) approach.<sup>133</sup> This approach may apply in situations where there are discontinuities or threshold effects, but there is considerable controversy about its validity. A related variant is to impose a reliability constraint, requiring that the odds of specified bad outcomes be kept below a set level.<sup>134</sup> The existence of threshold effects makes information about the location of thresholds quite valuable. For instance, in the case of climate change, a recent paper estimates that the value of early information about climate thresholds could be as high as 3% of gross world product.<sup>135</sup>

All of this may be very interesting (or not, depending on the reader's intellectual tastes.) The crucial question, however, is whether these various techniques can provide genuine assistance in dealing with important policy issues. Part III makes the case that uncertainty is central to some crucial policy issues and uses the techniques discussed above to shed light on those issues.

#### IV. Applying New Decision Techniques to Regulatory Policy

Part III showed that economic theory provides several different approaches to thinking about worst-case scenarios. First, we can consider whether fat tails characterize the probability distribution for harmful outcomes.<sup>136</sup> Second, we can use theories of ambiguity such as the  $\alpha$ -precautionary principle to analyze uncertainties. Third, we can use robust decision technique to locate strategies that function well under adverse

<sup>131</sup> *Id*.

<sup>134</sup> David McInerney & Klaus Keller, *Economically Optimal Risk Reduction Strategies in the Face of Uncertain Climate Thresholds*, 91 CLIMATIC CHANGE 29 (2007), *available at* <u>http://dx.doi.org/10.1007/s10584-006-9137-z</u>.

<sup>&</sup>lt;sup>132</sup> *Id*.

<sup>&</sup>lt;sup>133</sup> Michael Margolis & Eric Naevdal, *Safe Minimum Standards in Dynamic Resource Problems – Conditions for Living at the Edge of* Risk (RFF Discussion Paper 05-03, 2004), *available at* www.rff.org/RFF/Documents/RFF-DP-04-03.pdf. Margolis and Naevdal shows that "SMS is optimal policy if managers can put lower bounds on two parameters: the seriousness of the catastrophe and a parameter that determines how the magnitude of risk varies with the state-variable's position in state space." *Id.* at 3.

For discussion and critique of SMS, see Michael C. Farmer & Alan Randall, *The Rationality of a Safe Minimum Standard*, 74 LAND ECONOMICS 287 (1998) (arguing in favor of a "hard" version of SMS where a consensus exists that a resource is a human necessity); J.C. Rolfe, *Ulysses Revisisted – A Closer Look at the Safe Minimum Standard Rule*, 39 AUS. J. AG. ECON. 55 (1995) (arguing for a softer version in which SMS is understood as merely a switching rule triggering more intensive scrutiny of costs and benefits).

<sup>&</sup>lt;sup>135</sup> Klaus Keller et al., *What is the Economic Value of Information about Climate Thresholds?*, *in* HUMAN-INDUCED CLIMATE CHANGE: AN INTERDISCIPLINARY ASSESSMENT 349 Fig. 28.5 (Michael Schlesinger et al. eds 2007).

<sup>&</sup>lt;sup>136</sup> See supra text accompanying notes 84 to 101.

circumstances or we can eliminate strategies that violate minimum safe standards. We will deploy these tools in the context of some important current regulatory problems.

Part IV will consider five important social problems, each of which is characterized by considerable uncertainty:

(a) how much society should be willing to pay to mitigate climate change by reducing emissions of greenhouse gases;

(b) how society should plan to adapt to or reduce the impacts of whatever climate change does occur;

(c) whether society should restrict the development of nanotechnology;

(d) what to do with long-lived nuclear wastes; and

(e) how to prevent financial meltdowns like the one that occurred in 2009.

Each of these social problems in its own right presents a highly complex and technical set of issues. It would take a very long book rather than a single article to investigate all five in enough depth for an intelligent discussion of specific solutions. Rather than attempting that task here, this Article will merely demonstrate the existence of important uncertainties and show how the techniques discussed in Part III can help clarify the issues.

#### A. Climate Change Mitigation

Climate change is a prime example of a problem with large downside risks that are not well understood. To understand these risks precisely, we would need to be able to predict future climate developments with precision and confidently estimate the harmful effects of those climate changes. As it turns out, we can be fairly sure (though not completely certain) of the lower end of the potential temperature increase but not of the higher end; we are even less sure about the scale of impacts on humanity from higher temperature increases.

As Daniel Cole explains, the stumbling block is the "wide range of possible temperature increases . . . including a five-percent probability that temperature increases will equal or exceed 6° C and a two-percent probability of increases equal to or greater than 8° C within the next 100 to 200 years."<sup>137</sup> The reader may well want to know why these are merely probabilities. Why do we not *know* the future path of climate change?

Answering that question requires a more detailed discussion of the relevant climate science. The customary measure for how strongly the climate system responds to changes in the level of greenhouse gases is climate sensitivity. Climate sensitivity is measured as the equilibrium temperature increase caused by a permanent doubling of

<sup>&</sup>lt;sup>137</sup> Cole, *supra* note 2, at 75. Feedback effects, such as methane releases triggered by temperature increases, threaten to accelerate temperature changes. *See* Katey Walter Anthony, *Methane: A Menace Surfaces*, SCI. AMER. 69 ((December 2009).

preindustrial CO<sub>2</sub> concentrations.<sup>138</sup> Climate sensitivity is almost certainly greater than one degree centigrade, but there is between a two percent and a twenty percent chance that it exceeds five degrees.<sup>139</sup> A five-degree rise may not sound like much, but it is "equivalent to the change in average temperatures from the last ice age to today."<sup>140</sup>

Studies based on historical climate data find that climate sensitivity is unlikely to be below 1.5 °C; the upper bound is more difficult to determine for technical reasons – it could exceed 4.5 °C, although such high values are much less likely on the basis of the historical record than those in the 2.0 to 3.5 °C range.<sup>141</sup> A second line of research examines climate sensitivity in models. In each model, the climate sensitivity depends on many processes and feedbacks,<sup>142</sup> and probability distributions can be determined by examining how climate sensitivity tracks variations in various other parameters in the model. Essentially, parameters are subject to variations and the effect on climate response is measured through many runs of the model. The most frequent sensitivity values are around three degrees, but much higher values cannot be excluded.<sup>143</sup>

Unfortunately, there is no completely satisfactory way of translating these results into a formal probability distribution.<sup>144</sup> If we assume that all current models are equally likely and that they exhaust the possibilities, we can get a probability distribution, but these are somewhat heroic assumptions.<sup>145</sup> Consequently, however, it may be a mistake to assume that we can derive firm probability experts by comparing the outputs of current models.<sup>146</sup>

Even when models do agree, there are residual grounds for uncertainty. Models "are driven by similar forcing datasets, and hence might share a common error in, for

<sup>140</sup> Id. at xvi.

<sup>142</sup> The extent to which temperature increases lead to further releases of CO2 is disputed, but the most recent study of the historical record suggestions that this feedback loop is not terribly strong. *See* David C. Frank, *Ensemble Reconstruction Constraints on the Global Carbon Cycle Sensitivity to Climate*, 463 NATURE 527 (2010). The authors caution, however, that this estimate is based on pre-industrial conditions that may not apply today. *Id*. at 529.

<sup>143</sup> *Id.* at 799.

<sup>144</sup> *Id*.

<sup>145</sup> *Id*.

<sup>146</sup> As one climate scientist explains, "While ensemble projections carried out to date give a wide range of responses, they do not sample all possible sources of uncertainty. . . . More generally, the set of available models may share fundamental inadequacies, the effects of which cannot be quantified." *Id.* at 805.

<sup>&</sup>lt;sup>138</sup> STERN, *supra* note 2, at 10-11.

<sup>&</sup>lt;sup>139</sup> *Id.* at 13.

<sup>&</sup>lt;sup>141</sup> Gerald A. Meehl et al., *Global Climate Projections, in* INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS, CONTRIBUTION OF WORKING GROUP I TO THE FOURTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE 747, 800-01 (S. Solomon et al. eds., 2007), *available at* http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter10.pdf.

example, the amplitude of low-frequency solar variations."<sup>147</sup> Moreover, "at least until recently, the [climate science] community has been reluctant to treat the range of responses from available models as spanning the range of response that could be taking place in the real world," since models might share a common error in the way they represent climate processes.<sup>148</sup> There is fairly good evidence that there are no major missing factors, at least in terms of explaining overall Twentieth Century warming trends.<sup>149</sup> Nevertheless, we know that other factors are relevant and imperfectly modeled for future trends and regional impacts (as shown, for example, by the disagreements between models over the expected future degree of warming in various scenarios.)<sup>150</sup>

Some efforts have been made to quantify uncertainty based on various other lines of evidence.<sup>151</sup> New types of computational experiments have been performed to quantify uncertainty about how models respond to external inputs such as changes in solar intensity, including evidence about how uncertainties in estimates of processes that cannot be modeled fully "translate into the uncertainty in climate change projections."<sup>152</sup> This is accomplished, basically, by running models hundreds of times to see how the results differ.<sup>153</sup>

There is also the unknown degree of uncertainty involved with the human factor in modeling: the modelers themselves. Modelers and other scientists are prone to biases and errors, like the rest of us, despite the strenuous efforts that the scientific enterprise makes to limit the effects of these weaknesses.<sup>154</sup> This source of error is hard to estimate

<sup>149</sup> *Id.* at 1375.

<sup>150</sup> Meehl et al., *supra* note 141, at 797 (reference omitted). As the IPCC's review of the literature explains:

Uncertainty in prediction of anthropogenic climate change arises at all stages of the modeling process . . . The specification of future emissions of greenhouse gases, aerosols, and their precursors is uncertain. It is then necessary to convert these emissions into concentrations [of greenhouse gases], calculate the associate forcing [the direct temperature effect] and predict the response of climate system variables such as surface temperature and precipitation. At each step, uncertainty in the true signal of climate change is introduced both by errors in the representation of Earth system processes in models and by internal climate variability.

IPCC, GLOBAL CLIMATE PROJECTIONS, IN CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS: CONTRIBUTION OF WORKING GROUP I TO THE FOURTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE 747, 797 (2007) (references omitted).

<sup>152</sup> *Id*.

<sup>153</sup> Id.

<sup>&</sup>lt;sup>147</sup> Myles Allen et al., *Scientific Challenges in the Attribution of Harm to Human Influences on Climate*, 155 U. PA. L. REV. 1353, 1361 (2007).

<sup>&</sup>lt;sup>148</sup> *Id.* at 1361. "There is considerable debate over the extent to which currently available models span the range of plausible real-world responses." *Id.* 

<sup>&</sup>lt;sup>151</sup> Meehl et al., *supra* note 141, at 754.

<sup>&</sup>lt;sup>154</sup> See Mayanna Lahsen, Seductive Simulations? Uncertainty Distribution Around Climate Models, 35 SOC. STUD. OF SCI. 895 (2005).

and could easily operate in either direction: climate scientists may be under pressure to obtain dramatic results (thereby producing a bias in favor of large climate changes), but they may equally be under pressure to avoid anything that appears like sensationalism both in the interest of professionalism and to avoid attracting political attacks.

The upshot is that models give us a fair amount of confidence about basic trends but that we must be wary of assuming that their outputs are ironclad predictions of future developments. We can be highly confident about the existence of human-caused climate change and the likelihood that it will have serious effects. There is strong residual uncertainty, however, about the scale of climate change impacts, globally and regionally. This uncertainty might seem to argue against investing in climate change mitigation, but as demonstrated below, the possibility of high-impact scenarios actually provides a further reason to take precautionary steps.<sup>155</sup> As the Council of Economic Advisors wrote recently, "it is evident that policy based on the most likely outcomes may not adequately protect society because such estimates fail to reflect the harms at higher temperatures.<sup>156</sup>

In making policy decisions, we care not only about the physical impacts but also about their economic effects, the cost of mitigating climate change, and the cost of tempering impacts on humans through adaptation measures. Many individual elements of the economic impact analysis are the subjects of serious debate. For instance, some economists find an overall positive effect on US agriculture (but with very large regional variations),<sup>157</sup> while others find substantial negative effects.<sup>158</sup>

Modeling the systemic economic impact of climate change and the costs of adaptation and mitigation involves tremendous challenges, particularly if the projection

<sup>&</sup>lt;sup>155</sup> For an excellent general treatment of the treatment of uncertainty in policy analysis, see M. GRANGER MORGAN & MAX HENRION, UNCERTAINTY: A GUIDE TO DEALING WITH UNCERTAINTY IN QUANTITATIVE RISK AND POLICY ANALYSIS (1990). Granger and Menrion note that in settings "such as nuclear safety analysis" – and one might add climate change here – "where the tails of the distributions are of particular interest," reliance on the mean and variance as a basis for evaluating uncertainty can entail "a serious deficiency." *Id.* at 213. They prefer Monte Carlo sampling methods. *Id.* at 215.

<sup>&</sup>lt;sup>156</sup> U.S. Council of Economic Advisors, 2010 ECONOMIC REPORT TO THE PRESIDENT 242 (2010).

<sup>&</sup>lt;sup>157</sup> See Olivier Deschênes & Michael Greenstone, *The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather*, 96 AM. ECON. REV. 354, 381 (2007) (finding that the most likely result of climate change on American agricultural profits is an annual increase in profits of roughly 4 percent, but with California losing 15 percent). Note, however, that this study excludes possible impacts of increases in extreme events such as storms and droughts. *See id.* at 357–62. Extreme local events are a significant factor even in the absence of extreme global temperature changes. For instance, the latest models show indications of more-intense hurricanes in the remainder of this century. *See* Richard A. Kerr, *Models Foresee More-Intense Hurricanes in the Greenhouse*, 327 SCIENCE 399 (2010).

<sup>&</sup>lt;sup>158</sup> See Wolfram Schlenker, W. Michael Hanemann, & Anthony C. Fisher, *The Impact of Global Warming on U.S. Agriculture: An Econometric Analysis of Optimal Growing Conditions*, 88 REV. ECON. & STAT. 113, 122–24 (2006) (estimating the potential impact on farmland values east of the one-hundredth meridian for a range of warming scenarios and concluding that aggregate losses could be quite severe if fossil fuel use increases).

goes out more than a few years.<sup>159</sup> An expert at the Congressional Research Service indicated that "[1]ong-term projections . . . should be viewed with skepticism. . . . The finer the detail, the greater the skepticism should be."<sup>160</sup> Even the more confident economic modelers such as Nordhaus and Boyer<sup>161</sup> admit that attempts to estimate the impacts of climate change continue to be highly "speculative."<sup>162</sup> It is hard to forecast the trajectory of the economy over future decades —for example, no forecaster in 1970 would have predicted the explosive growth of personal computers, let alone the Internet, neither of which existed at the time, nor that complex financial derivatives, which also did not exist in 1970, would threaten a major economic depression early in the following century.

Past experience with models that project energy use do not lend much confidence to these predictions. The projections have generally been too high, by as much as a factor of two.<sup>163</sup> Predictive errors seem to stem in part from ignoring the tails of distributions, resulting in confidence intervals that are much too narrow.<sup>164</sup>

Forecasts also rely on inherently uncertain projections about future behavior. Forecasting future use of adaptation measures, is important in terms of determining the harms created by climate change. But this forecasting is impeded by the institutional barriers that may prevent optimal adaptation. For instance, the history of federal flood control gives little ground for optimism that flood control projects will be optimally designed.<sup>165</sup> Because climate change scenarios are based on projections of future

<sup>&</sup>lt;sup>159</sup> For a good overview of modeling issues, see J.C. Hourcade, et al., *Estimating the Costs of Mitigating Greenhouse Gases, in* CLIMATE CHANGE 1995: ECONOMIC AND SOCIAL DIMENSIONS OF CLIMATE CHANGE: CONTRIBUTION OF WORKING GROUP III TO THE SECOND ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE 268 (James P. Bruce et al. eds, 1996) (discussing the "critical determinants likely to influence the overall cost of climate policies and of the main methodologies employed to account for them

<sup>&</sup>lt;sup>160</sup> Darren Samuelson, *Climate: Uncertain Economic Models Create Headaches for Senate Panel*, ENV'T & ENERGY DAILY (Oct. 14, 2009), *available at* <u>http://www.eenews.net/Greenwire/2009/10/14/archive/5?terms=Climate%3A+Uncertain+Economic+Mode</u> <u>ls+Create+Headaches+for+Senate+Panel</u>.

<sup>&</sup>lt;sup>161</sup> WILLIAM D. NORDHAUS & JOSEPH G. BOYER, WARMING THE WORLD: ECONOMIC MODELS OF GLOBAL WARMING (2000).

<sup>&</sup>lt;sup>162</sup> *Id.* at 86 (conditioning their model on the need for a "detailed inventory and valuation of climatically sensitive regions for validation").

<sup>&</sup>lt;sup>163</sup> STEPHEN J. DECANIO, ECONOMIC MODELS OF CLIMATE CHANGE: A CRITIQUE 138–43 (2003) (reviewing the forecasts made in the 1980s by the US Department of Energy regarding global oil prices, and noting that within a single decade the forecasts had error rates of 100 to 200 percent).

<sup>&</sup>lt;sup>164</sup>See Alexander I. Shlyakhter, et al., *Quantifying the Credibility of Energy Projections from Trends in Past Data: The US Energy Sector*, ENERGY POL'Y 119 (1994).

<sup>&</sup>lt;sup>165</sup> See Matthew D. Zinn, Adapting to Climate Change: Environmental Law in a Warmer World, 34 ECOLOGY L.Q. 61, 72–73 (2007) (arguing that adaptation presents great institutional and political difficulties, which may prevent it from being successfully managed to minimize ecological or other impacts).

emissions, they implicitly make assumptions about future political and economic developments, which are imperfectly known (to say the least).

Outputs of various economic models are so far apart as to make it perilous to rely on any one model or even a small subset. According to a recent review, "cost estimates of Kyoto emissions reductions diverge by a factor of about five-hundred (and not all estimates show an economic loss)."<sup>166</sup> In any event, estimates of mitigation costs must be taken with a large grain of salt, which it makes it difficult to determine how much mitigation to require.

The more disturbing issues are on the scientific side and relate to the possibility that climate change will *not* be moderate. Based on an analysis of reported studies, Weitzman estimates that a "'best guess' estimate of the extreme bad tail" places the odds at about five percent of a temperature increase over ten degrees centigrade (eighteen degrees Fahrenheit) and a one percent change of an increase of twenty degrees (thirty six degrees Fahrenheit)."<sup>167</sup>

It is hard to improve on his explanation of the gravity of these findings. As he points out, "Societies and ecosystems in a world whose average temperature has changed in the geologically instantaneous time of two centuries or so [by these amounts] are located in *terra incognita*, since such high temperatures have not existed for hundreds of millions of years and such a rate of global temperature change might be unprecedented even on a timescale of billions of years."<sup>168</sup> Hence, "the planetary welfare effect of climate changes . . . implies a non-negligible probability of worldwide catastrophe."<sup>169</sup>

As Weitzman says, the normative implication is clearly a higher degree of precaution, making "insurance" against catastrophe a critical factor in climate policy.<sup>170</sup>

<sup>&</sup>lt;sup>166</sup> Philippe Tulkens & Henry Tulkens, *The White House and the Kyoto Protocol: Double Standards on Uncertainties and Their Consequence* \*8, figure 4 (FEEM Working Paper No 89, June 2006), *available at* http://ssrn.com/abstract=910811.

<sup>&</sup>lt;sup>167</sup> Weitzman, *supra* note 104, at 1.

 $<sup>^{168}</sup>$  Id. A leading critic of Weitzman, concurs that "[m]any people would agree that a 5 percent chance of a 10° change, or a 1 percent chance of a 20 ° change, would be a catastrophic prospect for human societies." William D. Nordhaus, An Analysis of the Dismal Theorem, available at http://ssrn.com/abstracts=1330454. Nordhaus contends, however, that the probabilities are lower. Id.

<sup>&</sup>lt;sup>169</sup> Weitzman, *supra* note 104, at 1.

<sup>&</sup>lt;sup>170</sup> Weitzman, *supra* note 104, at 18. The "fat tail" aspect of Weitzman's analysis seems to be crucial. Using a thin tail analysis while still taking into account possible extreme outcomes, Pindyck finds a case for moderate climate mitigation but nothing more. *See* Robert S. Pindyck, *Uncertain Outcomes and Climate Change Policy*, 10available at <u>http://ssrn.com/abstract=1448683</u> (last visited Jan. 24, 2010). Pindyck provides an important caveat: "We have no historical or experimental data from which to assess the likelihood of a ΔT [change in temperature] above 5 °C, never mind its economic impact, and one could argue a la Weitzman (2009) that we will never have sufficient data because the distributions are fat-tailed, implying a WTP [willing to pay] of 100% [of consumption] (or at least something much larger than 2%)." *Id.* at 22.

It is difficult to extract more specific guidance from his approach,<sup>171</sup> and we might instead turn to ambiguity-based models for guidance.

Ambiguity theory suggests that we weigh the best-case scenario (unimpeded economic growth combined with modest investment in climate adaptation) and the worst-case scenario (catastrophic climate outcomes), perhaps also including as a mid-case the standard economic models of climate change (which are optimistic and therefore not too far away from the best-case, as it happens).<sup>172</sup>

The implication of this analysis would be a high degree of precautionary catastrophe insurance, as Weitzman suggests. This argument can be seen as an application of Sunstein's "catastrophic harm precautionary principle."<sup>173</sup> Simply put, if we think in terms of  $\alpha$ -maxmin models, the worst case scenario if we do nothing is very grim, perhaps on the order of the end of civilization; the best case scenario is that harm from climate change is modest. Unless we are inclined to be very optimistic and place an extraordinarily heavy weight on the best case scenario, business as usual does not seem to be an appealing strategy – in fact, we should be willing to make major investments to reduce climate change. This conclusion is robust under a variety of assumptions, as shown below.

Specifically, if  $H_W$  is the harm in the worst case scenario and  $H_B$  is the harm in the best case scenario, we would attribute a cost of  $\alpha H_W + (1 - \alpha)H_B$  to the strategy of doing nothing. Even if  $H_B$  is zero (no net harm from climate change), the no-action option will not be appealing. The reason is that, since  $H_W$  is so large,  $\alpha H_W$  will be a large number unless  $\alpha$  is very small indeed. For example, suppose we are equally balanced between optimism and pessimism ( $\alpha = .5$ ) and that we take the worst case as being a temperature change equivalent to at least a trillion dollars in value. Then we would be willing to spend \$500 billion or more to avoid this risk.

If we take into account more catastrophic outcomes, the case for doing nothing evaporates even if we are quite optimistic about avoiding the worst-case scenario. As we have seen, Weitzman suggests that the most extreme outcomes could result in the end of

 $<sup>^{171}</sup>$  It is hard to quarrel, however, with Weitzman's statement that "[e]ven just acknowledging more openly the incredible magnitude of the deep structural uncertainties that are involved in climate-change analysis . . . might go a long way toward elevating the level of public discourse concerning what to do about global warming." Weitzman, *supra* note 104, at 18.

<sup>&</sup>lt;sup>172</sup> See supra text accompanying notes 108 to 123.

<sup>&</sup>lt;sup>173</sup> Cass R. Sunstein, *The Catastrophic Harm Precautionary Principle*, Issues in Legal Scholarship, Issue 10, Article 3, at 1–2 (2007), *available at* http://www.bepress.com/ils/iss10/art3. Another attempt to provide a rigorous basis for the precautionary principle can be found in Christian Gollier, Bruno Jullien, & Nicolas Treich, *Scientific Progress and Irreversibility: An Economic Interpretation of the 'Precautionary Principle*,' 75 J. PUB. ECON. 229, 239 (2000) (recommending precaution when "prudence is larger than twice absolute risk aversion"). *See also* J. Barkley Rosser, Jr, *Complex Ecologic-economic Dynamics and Environmental Policy*, 37 ECOLOGICAL ECON. 23, 32 (2001) (applying, among other theories, the precautionary principle to fishery management and commenting that "the Precautionary Principle is crucial in situations with critical threshold levels or effects").

civilization. If we just interpret that as a complete collapse of world GDP, we would get an estimated loss of  $10^{16}$  or a quadrillion dollars (or in more familiar terms, 1000 trillion.)<sup>174</sup> In order to reflect optimism about climate change, assume that the best case scenario is actually a 1 trillion benefit from warming, and take  $\alpha$ =.01 (meaning that we put ninety-nine times as much emphasis on the best case as the worst case). With some simple arithmetic, we come up with a loss figure of .01(1000 trillion) - .99(1 trillion) or approximately 9 trillion. Therefore, even if we are highly optimistic about the best case scenario a serious investment in climate mitigation would still be warranted if the downside risk is as severe as Weitzman suggests.

Thus, the  $\alpha$ -precautionary principle would warrant a high degree of precaution to avoid the negative uncertainties of climate change. Based on reasoning of this type, the Stern Report suggests that the cost of climate change should be assessed at between thirteen and twenty percent of current global consumption, with the weight used to average the figures being based on "crude judgments a out likelihoods of different kinds of probability distributions, on judgments about the severity of losses in this context, and on the basic degree of cautiousness on the part of the policy-maker."<sup>175</sup> The World Bank estimates world GDP in 2008 at about \$60.5 trillion,<sup>176</sup> so the value of eliminating climate change would be roughly \$6-12 trillion. Because Stern is only one model, the actual range of estimates is wider, making the choice of the weighting factor ( $\alpha$ ) even more important. It seems clear, however, that it would be worth investing a large amount of money in climate mitigation.

Indeed, even if the "best case scenario" is a *benefit* to society from climate change of \$1 trillion while keeping Stern's "worst case" of \$12 trillion (which as we have seenmay be far from most catastrophic outcome), and even if we choose a relatively lossaccepting  $\alpha$  of .25, we would obtain an estimated loss of [(-12 trillion + 1 trillion) x .25) = \$2.5 trillion. This would suggest that, in present value terms, we would be willing to make a fairly massive investment in climate change if doing so would eliminate the hazard.

It is tempting to seek a higher degree of precision in this recommendation, but in practical terms, the precision is probably irrelevant. If we take seriously that there is even a small possibility that climate change could wipe out our present society,<sup>177</sup> the

<sup>&</sup>lt;sup>174</sup> Nordhaus, *supra* note 168, at 14.

<sup>&</sup>lt;sup>175</sup> STERN, *supra* note 2, at 187. As Cole, *supra* note 2, explains, these numbers are controversial, but they are at least illustrative.

<sup>&</sup>lt;sup>176</sup> See World Bank, Key Development Data and Statistics, <u>http://web.worldbank.org/WBSITE/EXTERNAL/DATASTATISTICS/0,,contentMDK:20535285~menuP</u> <u>K:1390200~pagePK:64133150~piPK:64133175~theSitePK:239419,00.html</u>.

<sup>&</sup>lt;sup>177</sup> A caveat is that we could downplay the potential catastrophic possibilities if, as Nordhaus argues, we could learn that catastrophe is impending fast enough to make a sufficiently quick and vigorous global response to head off the possibility. *See* Nordhauas (Dismal Theorem), *supra* note 168, at 20. In my view, Nordhaus is excessively optimistic about this last-minute policy response, in part because of the potential for "climate surprises" involving abrupt climate change that might not leave a great deal of time for a

indicated amount of precaution is probably higher than anything we could plausibly expect from the political system. So the identity of the "correct" policy is this: the most stringent policy that is politically feasible.<sup>178</sup> Unfortunately, that policy still probably runs a haunting risk of catastrophe, but the best we can do is minimize that risk as much as we can bring society to embrace, hope things turn out well, and be prepared with other options if things are going sour.<sup>179</sup>

The basic lesson here is quite simple and does not depend on the details of the analysis. Climate policy cannot be based simply on the outcomes we consider most likely. The full range of possible consequences must be considered. Given the possibility of dire consequences from climate change, corrective measures should be supported even if those who believe that most likely climate change will not occur or that it will be beneficial.

#### B. Climate Change Adaptation

Even moderate climate change will have manifold effects: "increases in regional temperatures, changes in patterns of rainfall, rising sea levels, and increases in extreme events (heat waves, droughts, floods, storms)."<sup>180</sup> Adapting to these changes will not be cheap. In the developed world, the cost could run \$15-150 billion per year, assuming three or four degrees of global temperature rise.<sup>181</sup>

<sup>178</sup> As Robert Hahn explains:

[I]f one believes that the probability of a catastrophe is high, and the costs of a catastrophe are enormous, there may be a rationale for throwing the "kitchen sink" at the problem. For now, though, we have barely thrown anything at the problem, and the critical question facing politicians is what reasonable next steps in the real world might look like.

Robert W. Hahn, *Climate Policy: Separating Fact From Fantasy*, 33 HARV. ENV. L. REV. 558, 577 (2009). I believe that a high level of uncertainty, even without knowledge of a "high probability" is sufficient to justify strenuous climate mitigation efforts, but his point about the gap between the required response and the current situation is well taken.

<sup>179</sup> For this reason, despite its risks, geoengineering needs to be considered as a fallback measure if mitigation efforts are unsuccessfully in limiting climate change to non-catastropic levels. *See* Carolyn Kousky, Olga Rastaphova, Michael Toman, and Richard Zeckhauser, *Responding to Threats of Climate Change Mega-Catastrophes* (World Bank Policy Research Working Paper 5127 2009).

<sup>180</sup> STERN, *supra* note 2, at 466.

<sup>181</sup> *Id.* at 483. To get a sense of the potential economic impact, consider the following estimates regarding sea level rise: a half-meter sea level rise would place \$185 billion of property in jeopardy by 2100, and the cost protecting of developed areas from a half meter rise would be \$115 to \$274 billion.<sup>181</sup> WILLIAM E. EASTERLING III, BRIAN H. HURED, & JOEL B. SMITH, COPING WITH GLOBAL CLIMATE CHANGE: THE ROLE OF ADAPTATION IN THE UNITED STATES 14 (2004), available at <u>http://www.pewclimate.org/global-warming-in-depth/all\_reports/adaptation/</u> (last visited Jan. 24, 2010). This estimate may be on the high side, but even if we discount by a factor of two, the figures are still impressive.

response. *See* John D. Cox, CLIMATE CRASH: ABRUPT CLIMATE CHANGE AND WHAT IT MEANS FOR OUR FUTURE 189 (2005) ("The more likely circumstance . . . is that we are not going to predict the future with any degree of confidence – that climate surprises are inevitable.") Nevertheless, the potential for detecting and heading off catastrophic climate change does need to be considered as part of the analysis.

Adaptation is complicated by uncertainty about climate impacts.<sup>182</sup> Indeed, land managers list this as one of the most serious barriers to adaptation efforts.<sup>183</sup> Climate models differ in terms of the severity of climate change that they predict for any given future emissions path, and the future emissions path depends on mitigation limits that are not yet known.<sup>184</sup> Downscaling the models to predict local impacts introduces further uncertainties.

In the past, planners assumed that climate conditions were stable so that the past hydrological record provided a safe basis for planning, but that assumption is clearly outmoded.<sup>185</sup> For instance, both FEMA's flood control program and the Federal Crop Insurance Corporation have failed until very recently even to consider "the potential impacts of an increase in the frequency or severity of weather-related events on their operation."<sup>186</sup> Planners must now operate in a much more complicated world.<sup>187</sup> Investments that fare well under some future scenarios may do badly in others, and a major purpose is to choose investments that are resilient across the most relevant risks.

Uncertainty about future conditions is particularly relevant to large, long-term investments in infrastructure such as dams, water supply systems, or major power plants.<sup>188</sup> As a recent World Bank study states, "the design of infrastructure needs to take into account how climate conditions will evolve over the long-term, which is particularly difficult considering the uncertainty about local and regional patterns of climate change . ..."<sup>189</sup> The lead-time for new infrastructure is long. For instance, it took thirty years to

# <sup>185</sup> P.C.D. Milly et al., Stationarity is Dead: Whither Water Management, 319 Sci. 573 (2008).

<sup>186</sup> GAO, STRATEGIC FEDERAL PLANNING, *supra* note 183, at 43. FEMA is conducting a study of the issue that is scheduled to be complete in March 2010. *Id.* at 43 n.66.

<sup>187</sup> Adaptation of water systems includes a variety of responses. UNITED STATES GEOLOGICAL SURVEY, CLIMATE CHANGE AND WATER RESOURCES MANAGEMENT: A FEDERAL PERSPECTIVE 29-31 (Circular 1331, 2008). Some responses involve management of water systems through use of longer-range predictions to guide water reservoir use. Managing water demand is another option, including increased use of market transfer among users or conservation and efficiency improvements. It is also important to evaluate the risks to water infrastructure posed by more severe floods, which may require investment in existing dams and levees. Additional storage capacity (both surface and groundwater) may also be called for.

<sup>188</sup> Issues of climate adaptation for water projects are explained in LEVI D. BREKKE ET AL., CLIMATE CHANGE AND WATER RESOURCES MANAGEMENT: A FEDERAL PERSPECTIVE U.S. GEOLOGICAL SURVEY CIRCULAR 1331 (2009) (advocating the use of scenario planning).

<sup>189</sup> Stephane Hallegatte, Patrice Dumas, Jean-Charles Hourcade, *A Note on the Economic Cost of Climate Change and the Rationale to Limit it Below 2 C* (World Bank Policy Research Working Paper 5179, 2010).

<sup>&</sup>lt;sup>182</sup> STERN, *supra* note 2, at 466.

<sup>&</sup>lt;sup>183</sup> GENERAL ACCOUNTABILITY OFFICE, GAO-10-113, STRATEGIC FEDERAL PLANNING COULD HELP GOVERNMENT OFFICIALS MAKE MORE INFORMED DECISIONS 36-38 (2009).

<sup>&</sup>lt;sup>184</sup> For an extensive discussion of these uncertainties, see Daniel A. Farber, *Modeling Climate Change and Its Impacts: Law, Policy, and Science*, 86 TEX. L. REV. 1655, 1656–57 (2008) (discussing the difficulties of making public policy based on computer models that estimate the future effects of climate change).

build the flood barrier on the Thames, and the government recently issued a report mapping out maintenance and operation needs through 2070.<sup>190</sup> The long time spans involved with major infrastructure mean that decisions have to be made with an eye to future climate developments over at least several decades.

This kind of planning may require sorting through a large set of options. Suppose that a government is faced with a prospect of increased flood risks, but the amount is not clearly known. The options might include building higher or lower levees, either now or later when there is more information, or no additional levees (five options altogether); restricting development on floodplains, or not doing so (two options); changing building codes to improve resistance to flood damage or not doing so (two options); improving water storage capacity in order to hold flood waters or not doing so (two options); and improving water retention in upland areas by reducing impermeable surfaces in developed areas and expanding forested areas or not doing so (two more options). The ideal strategy probably involves some combination of these options. There are a total of  $5 \times 2 \times 2 \times 2 \times 2 = 90$  combination strategies available, and of course in reality each option comes with variations that would multiply the total further. We would like to know, for each combination strategy, how well it would fare in the high flood risk situation and the low flood risk situation, taking into account cost.

The RAND methodology for scenario analysis, which was discussed earlier,<sup>191</sup> is particularly helpful in locating robust strategies in this large set of possibilities. For instance, an analysis of water planning for Southern California revealed the need to provide greater resilience with respect to climate change and also identified methods of doing so by improving water use efficiency, expanding use of recycled water, and planning for greater capture of storm water to replenish aquifers.<sup>192</sup>

We have fairly good methods for analyzing situations in which risks can be quantified with reasonable confidence. We need improved methods for dealing with situations where such estimates do not exist or are subject to considerable uncertainty. The RAND methodology is a good start toward achieving such improved methodologies in planning adaptation to moderate climate change.

<sup>&</sup>lt;sup>190</sup> GAO, STRATEGIC FEDERAL PLANNING, *supra* note 183, at 37.

<sup>&</sup>lt;sup>191</sup> See supra text accompanying notes 127 to 138.

<sup>&</sup>lt;sup>192</sup> David G. Groves, Martha Davis, Robert Wilkinson, & Robert Lempert, *Planning for Climate Change in the Inland Empire: Southern California*, 10 WATER RESOURCES IMPACT 14 (July 2008). Scenario analysis may also help determine what factual issues are critical for deciding between options. This makes it possible to focus climate research on policy-relevant issues. We should not consider the degree of uncertainty to be fixed forever. One role of modeling is to help us identify research priorities which might reduce the range of uncertainties.

#### C. Nanotechnology

Nanotechnogy presents different sorts of unknowns and therefore a different context for investigating regulatory uncertainty. As a technology in its early stages of development, it presents the possibility of extraordinary benefits as well as serious risks. We have little ability to attach probabilities to any of the outcomes, making this a case of true uncertainty.<sup>193</sup>

Some background is in order. Nanotechnology is the domain of the remarkably small. One nanometer (nm) is equal to one-billionth of a meter (or about .00000004 inches), an incredibly tiny length. A single human blood cell is about seven thousand nanometers wide.<sup>194</sup> Nanoparticles do exist in the natural world and are produced as byproducts of human combustion activities.<sup>195</sup> The important point is that nanoparticles can have properties quite different from larger amounts of the same substance – for example, opaque particles can become transparent to visible light but reflective of ultraviolet light at nano size.<sup>196</sup>

Anticipated applications of nanotech in the relatively near-term include cosmetics, materials for remediating hazardous waste sites, fuel cells, video displays, batteries, and food additives; an array of longer-term development projects also exist.<sup>197</sup> But the same properties that make nanotech appealing may also pose risks: "concerns have been expressed that the very properties that are being exploited by researchers and industry (such as high surface reactivity and ability to cross cell membranes) might have negative health and environmental impacts, and particularly that they might result in greater toxicity."<sup>198</sup>

These risks are still poorly understood. A study by the Royal Society indicated that "there is a lack of information of their [nanomaterials'] health, safety, and environmental impact," requiring reliance on research results regarding other small particles from pollution and occupational research.<sup>199</sup> Given the uncertainties, the Royal

<sup>&</sup>lt;sup>193</sup> For a recent discussion that emphasizes the importance of these uncertainties, see Douglas A. Kysar, Ecologic: Nanotechnology, Environmental Assurance Bonding, and Symmetric Humility, available at <u>http://papers.ssrn.com/sol3/papers.cfm?abstract\_id=1464913</u> (forthcoming, UCLA Envtl. L. J.). For a short overview of the potential regulatory issues, see J. Clarence Davies, *Nanotechnology and Risk*, 172 REGULATION 11 (Summer 2009).

<sup>&</sup>lt;sup>194</sup> The Royal Society and Royal Academy of Engineering, Nanoscience and Nanotechnologies: Opportunities and Uncertainties 5 (2004).

<sup>&</sup>lt;sup>195</sup> *Id.* at 9.

<sup>&</sup>lt;sup>196</sup> *Id.* at 9.

<sup>&</sup>lt;sup>197</sup> *Id.* at 11-12.

<sup>&</sup>lt;sup>198</sup> ROYAL SOCIETY, *supra* note 194, at 35.

<sup>&</sup>lt;sup>199</sup> *Id.* at 47. As of 2004, according to the Royal Society, "very few studies have been published on the potential adverse effects that nanoparticles or nanotubes may have on humans, and only one to our knowledge on environmental effects." *Id.* at 75.

Society recommended a ban on use of free nanoparticles for cleaning up toxic sites<sup>200</sup> and it put a high priority investigation by regulators of the safety of nanoparticles in consumer products."<sup>201</sup>

On this side of the Atlantic, the Congressional Research Service (CRS) has also recently surveyed the risks and potential benefits of nanotechnology.<sup>202</sup> Since 2000, Congress has appropriated almost \$10 billion for nanotech research; in 2006, the public and private investment in nanotech was about twelve billion.<sup>203</sup> The CRS views current nanotech applications as "evolutionary in nature, offering incremental improvements in existing products and generally modest economic and societal benefits." In contrast, the long-run picture may involve revolutionary developments rather than incremental evolution: "nanotechnology may deliver revolutionary advances with profound economic and societal implications."<sup>204</sup> Examples including new tests and treatments for cancer; greatly improved renewable energy, universal access to clean water, and higher crop yields through use of nanosensors to detect plant diseases, along with a host of others.<sup>205</sup> Yet, CRS also recognizes risks. Scientists already know that some nanomaterials (carbon nanotubes and fullerenes) can cause lung damage in mice, brain damage in fish, and DNA damage.<sup>206</sup>

Environmental advocates call for a moratorium on commercial release of food and agricultural materials containing manufactured nanomaterials until a new legal structure is in place.<sup>207</sup> "Until we have a much more comprehensive understanding of the biological behavior of nanomaterials," they maintain, "it is impossible to predict the toxicity risks associated with any one material, and each new nanomaterial must be subject to new health and safety assessment prior to its commercial use."<sup>208</sup> Public interest groups "have invoked the Precautionary Principle in advocating a more draconian regulatory approach to address potential risks from nanomaterials."<sup>209</sup>

Others argue that the precautionary principles "freezes us in place," because "[n]o technology at its inception can satisfy the precautionary principle, so the principle

 $^{207}$  Friends of the Earth, Out of the Laboratory and On To Our Plates 3 (2008).

<sup>209</sup> David B. Fischer, *Nanotechnology – Scientific and Regulatory Challenges*, 19 VILL. L.J. 315, 331 (2008). Dana, *supra* note 71, argues that the precautionary principle may correct market incentives to avoid investigating possible environmental and health risks. *Id.* at 18-29.

 $<sup>^{200}</sup>$  Id. at 47.

<sup>&</sup>lt;sup>201</sup> Id. at 74.

<sup>&</sup>lt;sup>202</sup> JOHN F. SARGENT, JR., CONGRESSIONAL RESEARCH SERVICE, NANOTECHNOLOGY: A POLICY PRIMER (Feb. 2008).

<sup>&</sup>lt;sup>203</sup> *Id.* at Summary Page.

<sup>&</sup>lt;sup>204</sup> *Id.* at 1.

<sup>&</sup>lt;sup>205</sup> *Id.* at 3-4.

<sup>&</sup>lt;sup>206</sup> *Id.* at 9.

<sup>&</sup>lt;sup>208</sup> *Id.* at 5-6.

becomes a formula for doing nothing.<sup>210</sup> Thus, further study and investment in liability insurance are arguably better approaches.<sup>211</sup> Another possibility would be to impose a substantial bond requirement for substances that are allowed on the market after passing screening tests.<sup>212</sup>

Because nanotechnology has potential large upsides as well as downsides, an attitude of pure precaution seems inappropriate. Instead, we would do better to use ambiguity models that balance upside and downside outcomes, such as  $\alpha$ -maxmin.<sup>213</sup> The  $\alpha$ -precautionary principle would probably not justify efforts to forestall research and development of nanotechnology given its high upside potential. It would, however, justify a degree of caution.

An appropriate strategy could involve sustained research into health and safety issues of current uses of nanomaterials,<sup>214</sup> restrictions on uses involving potential public exposure until further risk information is available, and sensitivity to potential large downside risks in R & D for longer-term, non-evolutionary nanotechnologies. Given the unknown hazards associated with nanomaterials, it is surprising that regulatory authorities have failed to treat them as new substances for regulatory purposes, rather than giving them the more favorable treatment available to existing products.<sup>215</sup> That said, on balance nano materials do not require a more precautionary approach than new chemicals in general.

#### D. Nuclear Waste Disposal

The safe storage and disposal of nuclear waste is a serious, unsolved challenge. The most important waste stream from nuclear power plants is spent fuel. A large nuclear reactor produces 25–30 tons of spent fuel each year.<sup>216</sup> Safe disposal of this waste

<sup>&</sup>lt;sup>210</sup> Robin Fretwell, *Nanotechnology: The Challenge of Regulating Known Unknowns*, 34 J.L. MED. & ETHICS 704 (2006).

<sup>&</sup>lt;sup>211</sup> *Id.* at 711.

<sup>&</sup>lt;sup>212</sup> This proposal is made in Albert C. Lin, *Size Matters: Regulating Nanotechnology*, 11 HARV. ENVTL. L. REV. 349 (1007). Kysar, *supra* note 193, presents an alternative bonding proposal that emphasizes the role played by worst case outcomes in establishing bond amounts.

<sup>&</sup>lt;sup>213</sup> See supra text accompanying notes 118 to 125.

<sup>&</sup>lt;sup>214</sup> EPA has embraced such a research program, but if past practice is a guide, it could take a decade or more before the work even begins. This is not acceptable. *See* Editors, *Big Need for a Little Testing: The EPA Must Active Swiftly to Evaluate the Possible Health Risks of Nanotechnology*, SCIENTIFIC AMERICAN 20 (January 2010).

<sup>&</sup>lt;sup>215</sup> Diana M. Bowman & Graema A. Hodge, *A Small Matter of Regulation: An International Review of Nanotechnology Regulation*, 8 COLUM. SCI. & TECH. L. REV. 1, 36 (2007). An EPA advisory panel is now considering whether to recommend that nanosilver products be treated as new pesticides requiring a new pesticide registration. *See* Lynn L. Regeson, *FIFRA Scientific Advisory Panel Considers Nanosilver*, 39 ENV. L. REP. 11143 (2009).

<sup>&</sup>lt;sup>216</sup> C. W. FORSBERG, DEP'T OF ENERGY OAK RIDGE LABORATORY, ASSESSMENT OF NUCLEAR-HYDROGEN SYNERGIES WITH RENEWABLE ENERGY SYSTEMS AND COAL LIQUEFACTION PROCESSES (2006).

is critical. Presently, waste is stored at over a hundred facilities across the country, within seventy-five miles of the homes of 161 million people.<sup>217</sup>

The major problem is the longevity of the waste – plutonium will be dangerous for 250,000 years.<sup>218</sup> Although it is now considered feasible to model the geologic and physical processes at some geographic sites over such time periods, no one seems to have a clue about how to model possible changes in human behavior and society into the far future.<sup>219</sup> As one commentator has remarked, "[i]t is hard to comprehend the complexities that thinking along a 10,000-year timeline entails – nuclear waste did not exist 50 years ago, America did not exist 500 years ago, and recorded history did not exist 5000 years ago – but it certainly is not difficult to comprehend the uncertainty that accompanies such an extended timeline."<sup>220</sup>

The U.S. experience illustrates the pitfalls of finding a suitable method of permanent waste disposal. After much debate, Congress designated Yucca Mountain as the only potential site for permanent disposal.<sup>221</sup> The effort to establish a permanent site in Yucca Mountain ran into a wall of litigation<sup>222</sup> and political resistance. The Department of Energy (DOE) spent over \$8 billion in studying the site.<sup>223</sup>

In March of 2009, the project suffered a potentially fatal blow at the hands of the Obama administration, whose proposed budget fulfilled a campaign promise by cutting off nearly all the project's funding.<sup>224</sup> Despite this setback, as of early April 2009, the DOE was still moving forward with the facility's licensing proceedings, and as of January 2010, it had not withdrew its license application.<sup>225</sup> But even Republican Senator John McCain, a long-time proponent of the project, acknowledged that it might

<sup>223</sup> John L. Jurewitz, *The Current Outlook for the Nuclear Power Industry in the United States*, in INTERNATIONAL PERSPECTIVES OF ENERGY POLICY AND THE ROLE OF NUCLEAR POWER 227 (Lutz Mez, Mycle Schneider, & Steve Thomas eds. 2009).

<sup>224</sup> Matthew L. Wald, *Future Dim for Nuclear Waste Repository*, N.Y. TIMES, March 5 2009, at A15.

<sup>&</sup>lt;sup>217</sup> Reko Reblitz-Richardson, Comment, In Brief -- D.C. Circuit Rejects EPA's Proposed Standards and Extends Timeline for Yucca Mountain Nuclear Waste Repository, 32 ECOLOGY L.Q. 743 (2005).

<sup>&</sup>lt;sup>218</sup> *Id.* at 826.

<sup>&</sup>lt;sup>219</sup> *Id.* at 829.

<sup>&</sup>lt;sup>220</sup> *Id.* at 838.

<sup>&</sup>lt;sup>221</sup> See 42 U.S.C. § 10133(a), 10172(1-2).

<sup>&</sup>lt;sup>222</sup> Some of the major decisions include Nevada v. Herrington, 777 F.2d 529 (9<sup>th</sup> Cir. 1985); Nevada v. Burford, 708 F. Supp. 289 (D. Nev. 1989); Nevada v. Watkins, 914 F.2d 1545 (9<sup>th</sup> Cir. 1990); County of Esmeralda v. United States Dep't of Energy, 925 F.2d 1216 (9<sup>th</sup> Cir. 1991); Nevada v. United States, 133 F.3d 1201 (9<sup>th</sup> Cir. 1997); Nevada v. United States Dep't of Energy, 133 F.3d 1210 (9<sup>th</sup> Cir. 1998).

<sup>&</sup>lt;sup>225</sup> Alexandra Berzon, *Yucca Mountain; Energy Department presses for licenses as if nothing's changed*, LAS VEGAS SUN, April 4, 2009, at News 1; Katherine Ling, Yucca Haunts Admin's Lagging Efforts on Nuclear Waste Study Panel, N.Y. TIMES, Jan. 11, 2010, http://www.nytimes.com/gwire/2010/01/11/11greenwire-yucca-haunts-admins-lagging-efforts-on-nuclear-24943.html?pagewanted=1.

be politically doomed, and he urged Congress to "be honest with the American taxpayers and move forward on Yucca Mountain as we need to . . . or if not, close it and refund the money."<sup>226</sup> In any event, at best Yucca Mountain would be only a short-term solution. By 2036, the total amount of waste from existing plants would exceed the storage capacity at Yucca Mountain, assuming the facility were ever built.<sup>227</sup> Currently, U.S. nuclear waste disposal is in limbo.<sup>228</sup>

The Yucca Mountain plan was deceptively simple. Yucca Mountain is located in the desert about a hundred miles from Las Vegas, adjacent to the Nevada Test Site where nuclear bombs were tested.<sup>229</sup> The plan was to place the waste in containers consisting of a four-inch outer layer of carbon steel and a one-inch corrosion-proof inner layer.<sup>230</sup> The waste would be conveyed by unmanned vehicles to a series of tunnels hundreds of feet below the surface and also hundreds of feet above the water table.<sup>231</sup> The rock at the site was originally thought to be impermeable, but it turns out that fractures allow water percolation and that plutonium is surprisingly capable of traveling in water.<sup>232</sup> These details are significant for our purposes because they point out that science can hold surprises even on relatively mundane-seeming matters such as the percolation of water through rock. Recall that the NRC had been confident years earlier that water-tight containment would be possible.<sup>233</sup>

In its planning, the government excluded from consideration events that have less than a one in ten thousand chance,<sup>234</sup> which simplifies the task but at the possible cost of overlooking potential risks.<sup>235</sup> In essence, this amounted to eliminating any hazard that would not be likely to materialize in the next ten thousand years. Notice that this does not mean that the facility would actually be safe for ten thousand years. The fact that no *single* hazard is likely to materialize in the next ten thousand years does not necessarily mean that the *cumulative* probability of at least one of the risks materializing during that

<sup>232</sup> *Id.* at 834.

<sup>234</sup> *Id.* at 838.

<sup>&</sup>lt;sup>226</sup> Steve Tretuealt & Keith Roger, *McCain: Time for Yucca Plan B*, LAS VEGAS REV.-J., April 1 2009, at 1B.

<sup>&</sup>lt;sup>227</sup> Jurewitz, *supra* note 223, at 227.

<sup>&</sup>lt;sup>228</sup> See Katherine Ling, Yuca Haunts Admin's Lagging Efforts on Study Panel, Greenwire (January 11, 2010).

<sup>&</sup>lt;sup>229</sup> David P. Ross, Comment, Yucca Mountain and Reversing the Irreversible: The Need for Monitored Retrievable Storage in a Permanent Repository, 25 VT. L. REV. 815 (2001).

<sup>&</sup>lt;sup>230</sup> *Id.* at 821.

 $<sup>^{231}</sup>$  *Id*.

<sup>&</sup>lt;sup>233</sup> See supra text accompanying notes 30 to 34.

<sup>&</sup>lt;sup>235</sup> It may seem superficially plausible to exclude such remote risks, but some of the unlikely events could have such significant consequences that they are worth considering.

time is equally low.<sup>236</sup> Indeed, as we saw earlier, if the risks are fat-tailed, the cumulative probability might be substantially higher.<sup>237</sup>

As it turns out, ensuring safety for the next ten thousand years would not have been legally sufficient anyway. In *Nuclear Energy Inst., Inc. v. EPA*,<sup>238</sup> the Court held that the government had failed to justify departing from the recommendations of the National Academy of Science for a longer time period, recommendations that were entitled to EPA deference under the statutory scheme.<sup>239</sup> The court emphasized that the NAS had found no scientific basis for choosing the figure and that the peak radiation risks might not occur until much farther into the future.<sup>240</sup> The court also described as "odd" the government's decision that, "since it was 'impossible to predict either human activities or economic imperatives,' it would assume 'current conditions' would persist indefinitely."<sup>241</sup>

The only conclusion seems to be that the calculation of the physical likelihood of leakage should (hopefully) be reasonably accurate, the assumptions about human presence and activities in the area (and therefore about exposure) are speculative, and the likelihood of human interference with the integrity of the site is completely unknown. Perhaps we have no choice but to ignore these vast societal uncertainties in designing a specific disposal site. But the uncertainties are clearly relevant to deciding whether permanent geological disposal is the best solution or whether the waste problem is intractable enough to justify keeping the brakes on industry expansion.<sup>242</sup>

<sup>239</sup> *Id.* at 1273.

<sup>240</sup> As the court explained:

*Id.* at 1267.

<sup>241</sup> *Id.* at 1275.

 $<sup>^{236}</sup>$  Suppose that there are ten different risks, each of which is likely to materialize once in fifty thousand years. We would then expect some one of these risks to materialize about once every five thousand years, yet the government would not consider them in the analysis. Thus, excluding all events with a less than 1/10,000 probability does not guarantee the safety of the facility for even ten thousand years.

<sup>&</sup>lt;sup>237</sup> See supra text accompanying notes 94 to 101.

<sup>&</sup>lt;sup>238</sup> Nuclear Energy Inst., Inc. v. Envtl. Prot. Agency, 373 F.2d 1251 (D.C. Cir. 2004).

With respect to the length of the compliance period, NAS found "no scientific basis for limiting the time period of the individual-risk standard to 10,000 years or any other value." According to the Academy, "compliance assessment is feasible for most physical and geologic aspects of repository performance on the time scale of the long-term stability of the fundamental geologic regime – a time scale that is on the order of  $10^6$  [one million] years at Yucca Mountain." NAS also explained that humans may not face peak radiation risks until tens to hundreds of thousands of years after disposal, or even further into the future."

<sup>&</sup>lt;sup>242</sup> The problem of nuclear waste disposal has proved intractable even in France, despite that country's general enthusiasm for nuclear power. *See* Jon Palfreman, Why the French Like Nuclear Energy, <u>http://www.pbs.org/wgbh/pages/frontline/shows/reaction/readings/french.html</u> (last visited Jan. 24, 2010).

Yucca Mountain is not an edifying tale. Rebecca Bratspies describes Yucca Mountain as a paradigm example of the breakdown in the public's trust in regulatory agencies and their ability to make decisions in the face of uncertainty.<sup>243</sup> Citing a survey demonstrating that less than a third of the public trusted the federal government to be honest about its research in assessing the project's risks, Bratspies concludes the data "reveal a lack of trust in the objectivity and intellectual honesty of the decisionmakers, and suggest a clear perception that the research process was an attempt to drum up public support for an already crafted agenda, rather than a genuine attempt at dialogue and shared agenda building."<sup>244</sup> Given the NRC's track record of ignoring all hazards that it did not feel comfortable in quantifying, it is not hard to understand the public's lack of trust.

The NRC's optimism, discussed earlier, about finding a site for a permanent repository turns out to be a sad joke. Amanda Leiter has recently summarized what she calls the "pathetic" history<sup>245</sup> of Yucca Mountain, observing that "the federal government has had its eyes on Yucca Mountain for more than a quarter century, yet did not plan to break ground until 2011, waste disposal will not begin until 2017 at the earliest, and even that delayed timeline remains open to debate and modification . . . . As of 2017, the Yucca Project will have been in the works for forty years."<sup>246</sup> It is clear, in any event, that the promise that "no future generation would need to attend to our wastes" has proved "overly ambitious."<sup>247</sup>

The Yucca Project ran into political opposition for reasons that may have more to do with the NIMBY syndrome (Not in My Back Yard) than the challenges of multimillennial containment of waste. Nevertheless, the long-term challenges are truly daunting. Even routine engineering projects such as bridges have been known to unexpectedly fail. Yet those are projects that benefit from experience gained over many decades with many similar projects. In contrast, we have no experience whatsoever in engineering the containment of highly radioactive materials for tens of thousands of years.

Yet even those engineering risks are comparatively well understood in comparison with the societal risks. We are in little better position to forecast societal conditions in five thousand or ten thousand years than the builders of the early Egyptian pyramids would have been to forecast our own society. Perhaps our nuclear waste will

<sup>&</sup>lt;sup>243</sup> Rebecca M. Bratspies, *Regulatory Trust*, 51 ARIZ. L. REV. 575 (2009).

<sup>&</sup>lt;sup>244</sup> *Id.* at 626.

<sup>&</sup>lt;sup>245</sup> Amanda Leiter, *The Perils of a Half-Built Bridge: Risk Perception, Shifting Majorities, and the Nuclear Power Debate*, 35 ECOLOGY L.Q. 31, 61 (2008).

 $<sup>^{246}</sup>$  *Id.* at 63. Notably, even in France, where the public widely supports nuclear power: "When it came time to develop a waste facility, however, people balked. There were widespread demonstrations and even riots. And the problem has yet to be solved." *Id.* at 67.

<sup>&</sup>lt;sup>247</sup> Robert H. Socolow & Alexander Glaser, *Balancing Risks, Nuclear Energy and Climate Change*, DAEDALUS 31, 36 (2009).

be a valuable resource for a super-advanced technological society; perhaps the waste will provide raw materials for weapons of mass destruction to dangerous terrorists or warlords; perhaps the human race will be extinct or transformed beyond recognition. We simply do not know. The seriousness of these uncertainties is only intensified over time as the amount of nuclear waste grows.

In the short run, it is not feasible to eliminate existing nuclear facilities. We are then faced with what to do with the resulting waste. In considering strategies for disposing of the nuclear waste that we end up producing, something like the Rand RDM methodology may be useful in seeking robust solutions. The tougher problem is the basic question of whether to expand nuclear power and increase the production of waste.

In the medium run, we have to think seriously about the upside benefits of nuclear power and whether they are enough to counter the worst-case scenarios regarding release. Upside benefits seem likely mostly in terms of avoidance of carbon emissions to limit the severe downside risks of climate change.<sup>248</sup> Whether nuclear should be part of the medium-term strategy depends in part on how optimistic we are about alternate technologies (particularly with regard to need for base load power).<sup>249</sup> It is certainly possible that applying the  $\alpha$ -precautionary principle, which weighs best-case and worst-case outcomes, we might decide to keep nuclear power as part of our energy portfolio for the medium run.

In the long run, however, continued production of nuclear wastes seems unjustifiable given the tremendous uncertainties about containment – at least if we care significantly about the welfare of distant generations.<sup>250</sup> The more we expand and

<sup>&</sup>lt;sup>248</sup> The case for using nuclear power in this setting is made in Geoffrey Rothwell and Rob Graber, *The Role of Nuclear Power in Climate Change Mitigation*, in GENERATING ELECTRICITY IN A CARBON CONSTRAINED WORLD (Fereidoon P. Sioshansi ed. 2010). Rothwell and Graber have some concerns about the economics of rapidly ramping up nuclear power, but see it as a significant potential component of mitigation strategy:

<sup>[</sup>Nuclear power is the only central-station, GHG-free alternative that could replace global ever-growing ever-polluting coal-fired capacity. If utilities and nations are prepared to significantly increase their investment in nuclear power plant construction, nuclear power is capable of making an important contribution to GHG reduction and climate stabilization.

Id. at 205.

<sup>&</sup>lt;sup>249</sup> For discussion of the prospects of nuclear power expansion as a response to climate change, see Harold A. Feiverson, *A Skeptic's View of Nuclear Energy*, DAEDALUS 60 (Fall 2009); John W. Rowe, *Nuclear Power in a Carbon-Constrained World*, DAEDALUS 81 (Fall 2009); STEWART BRAND, WHOLE EARTH DISCIPLINE: AN ECOPRAGMATIST MANIFESTO (2009).

<sup>&</sup>lt;sup>250</sup> Whether we do so depends largely on whether we apply discounting to harms far in the future. Over long time periods, the results of changes in discount rates are enormous, as Cass Sunstein has explained, "[i]f a human life is valued at \$8 million, and if an agency chooses a 10% discount rate, a life saved 100 years from now is worth only \$581." Cass R. Sunstein, *Cost-Benefit Default Principles*, 99 MICH. L. REV. 1651, 1711 (2001). Imagine how little a life saved in 10,000 years is worth on this basis. Discounting is particularly controversial in the multigenerational context. For a review of the debate, see Daniel A. Farber, *From Here to Eternity*, 2003 U. ILL. L. REV. 289 (2003).

maintain our use of nuclear power, the more waste accumulates and the more serious the threat. There may be alternative ways of using nuclear reactions to produce power that do not result in the production of such long-lived, dangerous waste, or some way of destroying the waste more permanently may become practical. But as other non-carbon energy sources such as solar become more widespread and cost-effective, the upside benefits from conventional nuclear will fade, leaving us in a situation where  $\alpha$ -maxmin turns negative and requires avoidance of potential losses to future generations from large permanent repositories of nuclear waste.

The examples we have considered so far can all be considered environmental in some sense. The final example of fat tails and uncertainty, considered in the next subsection, goes further afield. It concerns a risk of economic rather than physical catastrophe.

#### E. Financial Regulation

Although this Article has focused on environmental applications, the problems of fat tails and true uncertainty are not limited to that context. Our final example involves the global financial system, which turns out to present analytical challenges not unlike that of climate change.

Judge Richard Posner observed in a 2009 book that "[t]he world's banking system collapsed last fall, was placed on life support at a cost of some trillions of dollars, and remains comatose."<sup>251</sup> He added: "We are in the midst of the greatest economic crisis since the Great Depression of the 1930s."<sup>252</sup> As most readers will recall, the crisis began with the bursting of the housing bubble and then transformed into a financial crisis.<sup>253</sup>

Ironically, much of the problem stemmed from financial instruments that were designed to tame risk. As Judge Posner pointed out, however, when the housing bubble burst, the nature of the situation changed from one of risk to one of uncertainty, making insurance of the kind offered through the derivatives markets a wild gamble.<sup>254</sup> As Posner

<sup>254</sup> "To understand how the difficulty of determining the riskiness of the new financial instruments contributed to the financial crisis, it is helpful to recall a distinction, made long ago by the economist Frank Knight, between two types of risk. One, which he called "risk," is a risk to which a probability can be assigned, and is the kind that insurance companies insure against because they can calculate a premium that will cover the risk. The other, called "uncertainty," is a risk that cannot be quantified. Anyone who insures such a risk is gambling; anyone who rates it (AAA, BB, etc.) is guessing." POSNER, *supra* note 251, at 60.

<sup>&</sup>lt;sup>251</sup> RICHARD A. POSNER, A FAILURE OF CAPITALISM: THE CRISIS OF '08 AND THE DESCENT INTO DEPRESSION vii (2009).

<sup>&</sup>lt;sup>252</sup> Id.

<sup>&</sup>lt;sup>253</sup> POSNER, *supra* note 251, at 13-14. For more detailed accounts of the crisis, see WILLIAM D. COHAN, A TALE OF HUBRIS AND WRETCHED EXCESS ON WALL STREET (2009); DAVID WESSEL, IN FED WE TRUST: BEN BERNANKE'S WAR ON THE GREAT PANIC (2009); Steven M. Davidoff & David Zarin, *Regulation by Deal: The Government's Response to the Financial Crisis*, 61 ADMIN. L. REV. 463, 471-512 (2009). A prophetic analysis can be found in CHARLES R. MORRIS, THE TRILLION DOLLAR MELTDOWN: EASY MONEY, HIGH ROLLERS, AND THE GREAT CREDIT CRASH (2008), while the classic study of similar historical episodes is CHARLES P. KINDELBERGER, MANIAS, PANICS, AND CRASHES: A HISTORY OF FINANCIAL CRISES (4th ed. 2000).

observed, a "choice under profound uncertainty is not adding a column of numbers but firing a shot in the dark."<sup>255</sup> Worse, it is a biased shot in the dark: Posner also noted that it is "tempting, indeed irresistible under conditions of uncertainty, to base policy to a degree on theoretical preconceptions, on a worldview, an ideology."<sup>256</sup> In the case of the Bush Administration, "[m]arkets were believed to be self-regulating, so the Securities and Exchange Commission could go to sleep. And go to sleep it did."<sup>257</sup>

In the terms used in this Article, what the banks and rating agencies had classified as a thin-tailed risk<sup>258</sup> turned out to have both fat tails and a great deal of ambiguity or uncertainty attached.<sup>259</sup> When the housing bubble burst, the "banks' uncertainty about their value of their mortgage-related assets and swap insurance and the magnitude of their swap liabilities curtailed – indeed, until the government stepped in, froze—lending."<sup>260</sup> There was clearly considerable feedback within the system – a drop in the relatively small part of the market tied to mortgage securities lead to massive market turnoil and financial collapse.<sup>261</sup>

A report by the International Monetary Fund (IMF) describes the feedback effects in detail.<sup>262</sup> The report uses a variety of methodologies.<sup>263</sup> Linkages within the financial center, according to the IMF, require regulators to "see beyond the immediate 'point of impact' by tracking several rounds of spillovers likely to arise from direct financial linkages."<sup>264</sup> The report contains an enlightening diagram of the complex risk linkages between key financial institutions.<sup>265</sup> Indeed, the IMF speaks of a credit event and

<sup>257</sup> *Id.* at 248, 274.

<sup>258</sup> For a discussion of conventional risk assessment methods, see Eric Talley & Johan Walden, *The Supervisory Capital Assessment Program: An Appraisal* (June 2009) (forthcoming).

<sup>259</sup> See supra text accompanying notes 94 to 101, and 108 to 113. See also JUSTIN FOX, THE MYTH OF THE RATIONAL MARKET: A HISTORY OF RISK, REWARD, AND DELUSION ON WALL STREET 134-135 (2009).

<sup>260</sup> POSNER, *supra* note 251, at 63.

<sup>261</sup> Kara M. Westercamp, A Crack in the Façade and the Whole Building Came Tumbling Down: A Critical Examination of the Central Banks' Response to the Subprime Mortgage Loan Crisis and Global Financial Market Turmoil, 18 TRANS. L. & CONTEMP. PROBS. 197, 215 (2009) ("The subprime market constituted only \$600 billion of the \$3 trillion mortgage business, yet the spillover has affected hedge funds, private equity, investment banks, commercial paper, and the stock market.").

<sup>262</sup> INTERNATIONAL MONETARY FUND, GLOBAL FINANCIAL STABILITY REPORT: RESPONDING TO THE FINANCIAL CRISIS AND MEASURING SYSTEMIC RISK (2009). One flaw in this report is that it acknowledges prior IMF appraisals were "too optimistic" but does not probe in detail the analytic weaknesses that led to this misappraisal of the situation. *Id.* at 6.

<sup>263</sup> The methodologies are summarized in the IMF report, and include a "network approach," a "co-risk model," a "distress dependence matrix," and a "default intensity model." *Id.* at 74.

<sup>264</sup> IMF, *supra* note 262, at 76.

<sup>265</sup> *Id.* at 90.

<sup>&</sup>lt;sup>255</sup> *Id.* at 83.

<sup>&</sup>lt;sup>256</sup> Id., at 134.

liquidity squeeze as "reverberating throughout the system."<sup>266</sup> There is also feedback between the general economy and the financial sector,<sup>267</sup> which may have increased in recent years,<sup>268</sup> and between geographic areas such as emerging and western Europe.<sup>269</sup>

Judge Posner views the financial collapse as an instance of "chaos theory"<sup>270</sup> – the theory of complex systems that are often characterized by power laws and fat tails.<sup>271</sup> Price fluctuations "exhibit fatter tails than the normal distribution,<sup>272</sup> and these fluctuations can be modeled with fractal geometry, a technique closely related to power law distributions.<sup>273</sup> Indeed, one study found that almost forty percent of market shifts lie outside of the normal Gaussian confidence intervals, with the highest five percent of market changes located over six standard deviations away from the mean.<sup>274</sup> The evidence seems very well established that stocks exhibit excess volatility, although the causes are controversial.<sup>275</sup> It appears that finance experts made a deliberate decision to ignore the fat-tail risks and focus solely on more probable (but less consequential) potential market movements.<sup>276</sup>

The financial collapse also reflected systemic effects – "effects that will be felt throughout the entire economic system," just as the "systemic effects of a trauma are those that involve the whole body."<sup>277</sup> Systemic effects can involve a jump from one

<sup>267</sup> *Id.* at xi.

<sup>269</sup> *Id.* at 12.

<sup>272</sup> Danielle A. Gordon & Daniel M. Kammen, Uncertainty and Overconfidence in Time Series Forecasts: Application to the Standard & Poor's 500 Stock Index, 6 APPLIED FINANCIAL ECONOMICS 189, 193 (1996).

<sup>273</sup> Benoit B. Mandelbrot, *A Multifractal Walk Down Wall Street*, SCIENTIFIC AMERICAN 70 (Feb. 1999). For a discussion of chaos and complexity theory and their possible applications to economics, see J. Barkley Rosser Jr., *On the Complexities of Complex Economic Dynamics*, 13 J. ECON. PERSP. 169 (Fall 1999). The present discussion does not rely on complexity theory except as a heuristic explanation for certain probability distributions; it is the distribution rather than the explanation that is most relevant.

<sup>274</sup> Gordon & Kammen, *supra* note 272, at 193.

<sup>275</sup> Barberis & Thaler, *supra* note 111, at 1075, 1078.

<sup>276</sup> See Justin Fox, The Myth of the Rational Market: A History of Risk, Reward, and Delusion on Wall Street 134-135 (2009).

<sup>277</sup> ROBERT J. SHILLER, THE SUBPRIME SOLUTION: HOW TODAY'S FINANCIAL CRISIS HAPPENED AND WHAT TO DO ABOUT IT 101 (2008).

<sup>&</sup>lt;sup>266</sup> *Id.* at 84.

<sup>&</sup>lt;sup>268</sup> *Id.* at 98 ("the sharp parallel increase in the economy-wide VaR [value at risk] and bank-wide VaR suggests a break with the past feedback patterns, indicating that macro-financial linkages are now tighter, potentially complicating the policy response to the financial sector problems.").

<sup>&</sup>lt;sup>270</sup> POSNER, *supra* note 251, at 131.

<sup>&</sup>lt;sup>271</sup> Id.

economic equilibrium to another.<sup>278</sup> The complexity and tight coupling of the economic system create serious potential instability in the markets.<sup>279</sup>

One lesson that Judge Posner – a long-time advocate of free markets and foe of government regulation – took from these events was this: "We are learning from [the crisis] that we need a more active and intelligent government to keep our model of a capitalist economy from running off the rails."<sup>280</sup> Posner attributed some of the mistakes leading to the current economic crisis in part to "an overinvestment by economists, policymakers, and business leaders in a free-market ideology that opposes aggressive government interventions in the operation of the economy."<sup>281</sup>

Without strong financial regulation, Posner says, "the rational behavior of lawabiding financiers and consumers can precipitate an economic disaster."<sup>282</sup> The IMF, too, maintains that "improved financial regulation and supervision are key components to preventing future crises," with an emphasis on "how to detect and mitigate systemic risks through better regulation."<sup>283</sup>

The question of how to regulate financial markets is far too large to attempt to answer here.<sup>284</sup> The key point is simply that reforms must take into account not only the "normal" behavior of the market but the fat tailed nature of stock movements, which mean that extraordinary fluctuations have to be expected and guarded against. One method of doing so is the use of stress tests of financial models using worst-case scenarios or "back testing" using historical data.<sup>285</sup> Because financial regulation may involve many possible combinations of rules, and because it is hard to be confident about the exact form of future stresses on the system, something like the RAND computerized scenario system might be useful in helping to establish portfolios of regulatory measures that are robust. Given the fat-tailed nature of the probability distributions governing financial markets, it would be foolhardy to assume that the 2009 meltdown was an isolated incident or even that it reflects the worst case scenario.

<sup>284</sup> HAL S. SCOTT, THE GLOBAL FINANCIAL CRISIS (2009) (reviews responses to the financial crisis and various reform proposals).

<sup>285</sup> See Erik F. Gerding, Code, Crash, and Open Source: The Outsourcing of Financial Regulation to Risk Models and the Global Financial Crisis, 84 WASH. L. REV. 127 (2009). "Back testing" involves "modelers making several hypothetical jumps back in time, inputting historical data that were available at those respective times, and then comparing the predictions of the model with how losses actually unfolded." *Id.* Efforts at stress-testing banks after the financial meltdown are discussed in Talley & Walden, *supra* note 258.

<sup>&</sup>lt;sup>278</sup> *Id.* at 104.

<sup>&</sup>lt;sup>279</sup> BOOKSTABER, *supra* note 4, at 144-145.

<sup>&</sup>lt;sup>280</sup> POSNER, *supra* note 251, at xii.

<sup>&</sup>lt;sup>281</sup> *Id.* at 260.

<sup>&</sup>lt;sup>282</sup> *Id.* at 107.

<sup>&</sup>lt;sup>283</sup> IMF, *supra* note 262, at xxii. For a discussion of reform efforts aimed at the subprime market that triggered the crisis, *see* SHILLER, *supra* note 277 at 107-169.

#### V. Conclusion

Our society faces serious problems, many of which would be difficult to manage under the best of circumstances.<sup>286</sup> Addressing these problems is all the more difficult because they often involve threatened harms whose dimensions are only understood imperfectly. In particular, we are often unable to quantify the probability of harm with any confidence. It is sometimes tempting to ignore such hazards as speculative. That is clearly the wrong response. Just because you do not know exactly how big a number is, there is no reason to assume it to be zero. (Q: What is the GDP of China? If you don't know, should you guess zero?)

A better response would be to use some variety of the precautionary principle, which at least keeps the threatened harm on the agenda and counsels caution in dealing with it. But the precautionary principle, or even the catastrophic risk precautionary principle advocated by Sunstein, falls well short of providing concrete guidance.<sup>287</sup> This Article has explored developments in economic theory that may provide more clarity in dealing with unquantifiable uncertainties.

As we have seen, such uncertainties can be associated with fat tailed distributions – either because we know the distribution and the expected risk or its variance turn out to be infinite, or because the nature of the distribution prevents us from setting key parameters accurately enough to determine the expected risk or variance.<sup>288</sup> There is some reason to think that, because of internal feedbacks, both climate change and financial crashes may have such characteristics.

In other situations, we may simply have no good idea of how to assign probabilities in the first place or of what the probability distribution might look like. In those situations, we need to think about a variety of possible scenarios. Examples include estimates of the medium-run risks and benefits of nanotechnology,<sup>289</sup> or the long-term risks of nuclear waste disposal.<sup>290</sup> Ambiguity theory helps address these situations, and the most easily applied models advise assessing decisions based on a combination of the best-case and worst-case scenarios. This leads to the  $\alpha$ -precautionary principle, which weighs the best and worst potential outcomes in assessing a course of action.

One lesson of this investigation into non-quantifiable hazards is that uncertainty is not unitary but plural. Former Secretary of Defense Donald Rumsfeld famously

<sup>&</sup>lt;sup>286</sup> Other applications exist beyond those discussed in this article. For instance, the question of whether to remove a child from a possibly abusive parent involves great uncertainties about the potentially severe harm to the child from remaining with the parent as well as the psychological harm of removing the parent. Counter-terrorism is another obvious application, as are measures to prepare for catastrophic events such as Hurricane Katrina.

<sup>&</sup>lt;sup>287</sup> See supra text accompanying notes 56 to 71.

<sup>&</sup>lt;sup>288</sup> See supra text accompanying notes 102 to 106.

<sup>&</sup>lt;sup>289</sup> See supra text accompanying notes 193 to 209.

<sup>&</sup>lt;sup>290</sup> See supra text accompanying notes 216 to 250.

distinguished between known knowns, known unknowns and unknown unknowns, with the latter being the most worrisome.<sup>291</sup> The "known knowns" correspond not merely to certainties but to probability distributions that are well understood – risks, rather than uncertainties, in the lexicon of this article.

But the known unknowns fall into several categories. Some are known in the sense that we have a grasp on the shape of the probability distribution but not key parameters – and in some cases, the key parameters turn out to be difficult to determine or even unknowable. There are also risks that we know are unknowable, such as the evolution of human society over future millennia.<sup>292</sup> These known unknowables merge into the Rumsfeld's category of unknown unknowns.

Yet, in some cases we may have a handle on even the unknown unknowns. For instance, we may not have a good understanding of which particular future shocks might affect a system. Nevertheless, understanding the feedbacks in the system and the statistical distribution of outcomes might enable us to understand how the system will respond even to unknown shocks. Uncertainty, then, is a multidimensional concept.

It would certainly be nice if economics were to provide a foolproof way of making decisions under conditions of uncertainty, given the importance of those decisions for society. The prospects for such a development are themselves – there is no other way to put this – highly uncertain, and they are all the more so because uncertainty takes so many forms. Certainly, no such methodology now exists, and one might well question whether it is even possible. But an analytical tool need not be decisive to still be useful.

Complicated but potentially catastrophic problems like global climate change or financial crashes will always present difficult choices, once we at least get to the point of acknowledging that these threats are real and must be dealt with. There is no easy recipe for divining the right solution to problems whose parameters involve so much uncertainty. We cannot afford to ignore perils simply because their probability is uncertain, nor can we safely proceed on the basis of speculative numerical estimates. But we can gain some much-needed clarity with the tools discussed in this article.

<sup>&</sup>lt;sup>291</sup> "[A]s we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns -- the ones we don't know we don't know. And if one looks throughout the history of our country and other free countries, it is the latter category that tend to be the difficult ones." DoD News Briefing -Secretary Rumsfeld and Gen. Myers (Feb. 12. 2002), available at http://www.defenselink.mil/transcripts/transcript.aspx?transcriptid=2636.

<sup>&</sup>lt;sup>292</sup> See supra text accompanying notes 247 to 250.