Ecologic: Nanotechnology, Environmental Assurance Bonding, and Symmetric Humility

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Abstract. To date, the turn toward market-based regulatory tools in the environmental, health, and safety context has tended to focus on taxes, tradable permits, and information disclosure rules, with comparatively little attention devoted to environmental assurance bonds. This paper argues that environmental assurance bonding offers a particularly attractive regulatory approach for contexts – such as the present state of nanoscale science and engineering – in which both the risk and the benefit sides of the regulatory equation are characterized by great uncertainty. Historical examples and existing scholarly analyses of environmental assurance bonding are reviewed, and the resulting lessons are situated within the larger debate over economic cost-benefit balancing and precautionary approaches to environmental law and policy. In particular, the paper argues that environmental assurance bonding displays the virtue of symmetric humility, paying due heed to the dynamism and complexity both of sociolegal systems such as markets and of biophysical systems such as aquatic ecosystems.

* Professor of Law, Yale University. This article benefited greatly from research assistance provided by Tafari Lumumba. For helpful comments and suggestions on an earlier version, I thank . . . and the participants of the UCLA 2009 Working Conference on Nanotechnology Regulatory Policy. All misjudgments, errors, and omissions are my own.

Introduction

"Human history becomes more and more a race between education and catastrophe."

-- H.G. Wells, Outline of History (1920)

On January 30, 2009, U.S. President Barack Obama issued a memorandum to the heads of executive departments and agencies expressing an intention to study and revise the manner in which the Office of Information and Regulatory Affairs (OIRA) within the Office of Management and Budget (OMB) conducts regulatory impact review, including economic cost-benefit analysis of proposed rules. He wrote:

> The fundamental principles and structures governing contemporary regulatory review were set out in Executive Order 12866 of September 30, 1993. A great deal has been learned since that time. Far more is now known about regulation – not only about when it is justified, but also about what works and what does not. Far more is also known about the uses of a variety of regulatory tools such as warnings, disclosure requirements, public education, and economic incentives. Years of experience have also provided lessons about how to improve the process of regulatory review. In this time of fundamental transformation, that process – and the principles governing regulation in general – should be revisited.
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> I therefore direct the Director of OMB, in consultation with representatives of regulatory agencies, as appropriate, to produce within 100 days a set of recommendations for a new Executive Order on Federal regulatory review. Among other things, the recommendations should offer suggestions for the relationship between OIRA and the agencies; provide guidance on disclosure and transparency; encourage public participation in agency regulatory processes; offer suggestions on the role of cost-benefit analysis; address the role of distributional considerations, fairness, and concern for the interests of future generations; identify methods of ensuring that regulatory review does not produce undue delay; clarify the role of the behavioral sciences in formulating regulatory policy; and identify the best tools for achieving public goals through the regulatory process.

Under pressure from nongovernmental organizations such as the Center for Progressive Reform,[1] the Executive Order review process was opened up for broader public comment.

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The resulting input suggests that, despite the President's suggestion that "a great deal has been learned" regarding the design and impact of regulations, civil society remains deeply split regarding the desirability of regulatory cost-benefit analysis (CBA) as a tool for evaluating proposed policies.[2] Numerous commentators focused their suggestions on incremental methodological improvements to CBA, expressing unequivocal support for the core idea of evaluating the content of policies based on their predicted overall impacts for human well-being. Several others, however, raised serious moral and political objections to the use of the CBA methodology. They offered instead a vision of policymaking much more pluralistic in its conception of value and much more pragmatic in its assumptions regarding the availability and certitude of empirical knowledge regarding policy effects. Although these commentators tended not to invoke the principle by name, their recommendations followed a course that internationally has come to be associated with the Precautionary Principle (PP).[3]

[2] These comments are available at http://www.reginfo.gov/public/jsp/EO/fedRegReview/publicComments.jsp.

[3] The PP is a decision heuristic that counsels erring on the side of safety when scientific uncertainty exists over the potential consequences of an action. Principle 15 of the Rio Declaration attempts to capture the desired relationship between the PP and environmental law:

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

United Nations Conference on Environment and Development, Declaration of Principles, 31 I.L.M. 874 (1992). Despite this international recognition, the PP remains somewhat ill-formed in policy discussions. As one commentator put it, "though the precautionary principle provides a useful overall orientation, it is an insufficient basis for policy and largely lacks legal content." Daniel Bodansky, Commentary: The Precautionary Principle, Environment, April 1992, at 4. Defenders of the principle contend that it appears ill-formed or devoid of content only when evaluated from the very formalistic and rationalist vantage point that the principle aims to critique. *See, e.g.,* Jordan & O'Riordan, p. 16 ("Like sustainability, [the PP] is neither a well-defined nor a stable concept. Rather, it has become the repository for a jumble of adventurous beliefs that challenge the status quo of political power, ideology and environmental rights. Neither concept has much coherence other than is captured by the spirit that is challenging the authority of science, the hegemony of cost-benefit analysis, the powerlessness of the victims of environmental abuse, and the unimplemented ethics of intrinsic natural rights and intergenerational equity. It is because the mood of the times needs an organizing idea that the precautionary principle is getting attention.").

The divide between supporters of CBA and the PP is related to a more general split found within environmental law and policy circles, one so stark and staunchly policed as to occasionally resemble a world of environmental tribalism.[4] In this world, proponents of "cool analysis" and "moral outrage,"[5] or what Christopher Schroeder calls environmental "priests" and "philosophers,"[6] seem unwilling to alter or compromise their positions, leading to a perception that the debate over environmental, health, and safety regulation is based on philosophical differences that simply cannot be overcome. Daniel Farber, for instance, worries that the conflict between "tree huggers" and "bean counters" reflects a divide over whether environmental law and policy should be determined by "willingness to vote" or "willingness to pay" that is simply insurmountable.[7] Of late, those on the "moral outrage"/"philosopher"/"tree hugger" side of the environmental law and policy divide have come in for harsh critique and commentary from their opponents, suggesting that supporters of the economic approach are seeking a total victory, rather than agreement on some integrated compromise. Supporters of CBA, for instance, have dismissed the PP in especially strident terms, describing the principle as "incoherent,"[8] "indeterminate,"[9] "paralyzing,"[10] and "literally senseless."[11] Indeed, proponents of CBA have begun to declare

[4] *See* Kysar & Salzman, *supra* note __, at __.

[5] ROBERT V. PERCIVAL ET AL., ENVIRONMENTAL REGULATION: LAW, SCIENCE, AND POLICY 73 (3d ed. 2000).

[6] Christopher H. Schroeder, *Prophets, Priests and Pragmatists*, 87 MINN. L. REV. __ (2003).

[7] FARBER, *supra* note __, at 39-42.

[8] Todd J. Zywicki, *Baptists?: The Political Economy of Environmental Interest Groups*, 53 CASE WES. L. REV. 315, 333 (2002).

[9] Stone, *supra* note __, at 10799.

[10] Sunstein, *Beyond the Precautionary Principle*, *supra* note __, at 1004.

[11] *Id.* at 1008. For further critical commentary regarding the PP, see Sunstein, *Beyond the Precautionary Principle*, *supra* note __; Jonathan B. Wiener, *Precaution in a Multi-Risk World*, in HUMAN AND ECOLOGICAL RISK ASSESSMENT: THEORY AND PRACTICE 1509 (Dennis D. Paustenbach ed., 2002); M. GOKLANY, THE PRECAUTIONARY PRINCIPLE: A CRITICAL APPRAISAL OF ENVIRONMENTAL RISK ASSESSMENT (2001); Christopher D. Stone, *Is There a Precautionary Principle?*, 31 ENVTL. L. REP. 10790 (2001); Adler, *supra* note __; HOWARD MARGOLIS, DEALING WITH RISK 75-79 (1996); Frank B. Cross, *Paradoxical Perils of the Precautionary*

victory for themselves, describing the "first generation debate" regarding CBA's basic normative desirability as over, and asserting that the important questions today concern "second generation" issues regarding how best to implement CBA in the risk regulation context.[12]

In a forthcoming book,[13] I defend the conceptual coherence and normative desirability of policy approaches, such as those associated with the PP, that reject the idea that environmental, health, and safety law ever can be adequately addressed from an assumed viewpoint of objectivity. The danger, I argue, is that the attempt to render environmental, health, and safety regulation fully determinable through empirical assessment and formalized decisionmaking models – an attempt found most influentially in the methodology of CBA, but associated more generally with the economic regulatory reform project of the last three decades – obscures the relation of agency and responsibility that the political community bears to its decisions. Even robust institutional actors such as nation-states confront forces that lie beyond complete prediction and control, such as the operations of natural systems that escape precise probabilistic understanding, the actions of foreign nations and other non-subjects that depend on and impact shared resources, and the future needs and circumstances of unborn generations that are a necessary, but unknowable feature of any policy decision involving intergenerational consequences. I argue that, within such a decisionmaking context, the political community must always in a nontrivial sense stand outside of its tools of policy assessment, maintaining a degree of self-awareness and

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Principle, 53 WASH. & LEE L. REV. 851 (1996); JOHN D. GRAHAM & JONATHAN BAERT WIENER, RISK VERSUS RISK (1995).

[12] CASS R. SUNSTEIN, THE COST-BENEFIT STATE xi (2002). *See also* CASS R. SUNSTEIN, RISK & REASON: SAFETY, LAW, AND THE ENVIRONMENT (2002) at 5-6 (asserting that "'first-generation' debate about whether to base regulatory choices on cost-benefit analysis at all . . . is now ending, with a substantial victory for the proponents of cost-benefit analysis").

[13] Douglas A. Kysar, Regulating from Nowhere: Environmental Law and the Search for Objectivity (under contract, Yale University Press, forthcoming 2010).

self-criticality regarding the manner in which its agency is exercised. The PP encourages such conscientiousness by reminding the political community, as it stands poised on the verge of a policy choice with potentially serious or irreversible environmental consequences, that its actions *matter*, that they belong uniquely to the community and will form a part of its narrative history and identity, helping to underwrite its standing in the community of communities that includes other nations, other generations, and other forms of life. Such considerations, in contrast, hold no clear or secure place within the logic of cost-benefit optimization, tending as it does to deny the political community a view from within itself, and to ask the community, in essence, to regulate from nowhere.

This Article seeks to make a more modest, but also more grounded contribution: It argues that the turn toward market-based policy instruments in environmental, health, and safety law has focused unduly on the use of pollution taxes and tradable permits, and that a third market-based instrument, the *environmental assurance bond*, offers features that should commend it both to "tree huggers" and to "bean counters," to "philosophers" and to "priests." Especially in the context of a nascent field such as nanoscale science and engineering, within which available information regarding potential consequences is highly incomplete and uncertain, the environmental assurance bond is a normatively attractive policy tool because it displays the virtue of *symmetric humility*.[14] Promoters of CBA support

[14] Albert Lin has also argued that environmental assurance bonding offers an especially attractive policy approach for the burgeoning field of nanoscale science and engineering, which is characterized by uncertain but potentially dramatic effects, both in terms of the benefits it promises and the harms it threatens. *See* Albert C. Lin, *Size Matters: Regulating Nanotechnology*, 31 HARV. ENVTL. L. REV. 349 (2007). For other analyses of regulatory aspects of nanoscale science and engineering, see NANOTECHNOLOGY AND THE ENVIRONMENT (Kathleen Sellers, Christopher Mackay, Lynn Bergeson, Stephen Clough, Marilyn Hoyt, Julie Chen, Kim Henry, & Jane Hamblen, eds., 2008); Kenneth W. Abbott, Gary E. Marchant, & Douglas J. Sylvester, *A Framework Convention for Nanotechnology?*, 38 ENVTL. L. REP. NEWS & ANALYSIS 10507 (2008); Gregory Mandel, *Nanotechnology Governance*, 59 ALA. L. REV. 1323 (2008); David B. Fischer, *Nanotechnology -- Scientific And Regulatory Challenges*, 19 VILL. ENVTL. L.J. 315 (2008); James Yeagle, *Nanotechnology and the FDA*, 12 VA. J.L. & TECH 6 (2007); Gary E. Marchant & Douglas J. Sylvester, *Transnational Models For Regulation Of Nanotechnology*, 34 J.L. Med. & Ethics 714 (2006); Robin Fretwell Wilson, *Nanotechnology: The Challenge Of Regulating Known Unknowns*, 34 J.L. Med. & Ethics 704 (2006); Linda K. Breggin, Leslie Carothers, *Governing*

analytical requirements for regulators that presuppose simplicity, predictability, and manipulability in the environment. In essence, they support something like central planning for the environment, even though they would abhor such planning in the economy. Regulatory reformers do so because they believe that economic incentives are sufficiently powerful – and private interactions sufficiently reliable – to promote overall human well-being with greater success than fallible and corruptible government agencies. Hence, in their view, regulators should be required to overcome a substantial burden of proof before interfering with the dynamism and complexity of the market. Conversely, PP proponents recommend precautionary and protective regulation because they appreciate the fragility and interconnectedness of ecological systems. Hence, they would place a substantial burden of

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Uncertainty: The Nanotechnology Environmental, Health, And Safety Challenge, 31 Colum. J. Envtl. L. 285 (2006); Francisco Castro, *Legal And Regulatory Concerns Facing Nanotechnology*, 4 Chi.-Kent J. Intell. Prop. 140 (2004); K. Eric Drexler & Jason Wejnert, *Nanotechnology and Policy*, 45 Jurimetrics J. 1 (2004); Glenn Harlan Reynolds, *Nanotechnology and Regulatory Policy: Three Futures*, 17 HARV. J. L. & TECH. 179 (2003); Glenn Harlan Reynolds, *Environmental Regulation of Nanotechnology*, 31 ENVTL. L. REP. 10681 (2001).

For analyses of environmental assurance bonds as regulatory compliance tools, see David Gerard & Elizabeth J. Wilson, *Environmental Bonds and the Challenge of Long-Term Carbon Sequestration*, 90 J. ENVTL. MGMT. 1097 (2009); Robert F. Blomquist, *Models and Metaphors for Encouraging Responsible Private Management of Transboundary Toxic Substances Risk: Toward a Theory of International Incentive-Based Environmental Experimentation*, 18 U. PA. J. INT'L ECON. L. 507 (1997); Monique Lee Hawthorne, *Confronting Toxic Work Exposure in China: The Precautionary Prinicple and Burden-Shifting*, 37 ENVTL. L. 151 (2007); D.F. Ferreira & S.B. Suslick, *Identifying the Potential Impacts of Bonding Instruments on Offshore Oil Projects*, 27 Resources Pol'y 43 (2001); David Gerard, *The Law and Economics of Reclamation Bonds*, 26 RESOURCES POL'Y 189 (2000); David R. Hodas, *The Role of Law in Defining Sustainable Development: NEPA Reconsidered*, 3 WIDENER L. SYMP. J. 1 (1998); MICHAEL COMMON, SUSTAINABILITY AND POLICY: LIMITS TO ECONOMICS (1995); Dana Clark & David Downes, *What Price Biodiversity? Economics Incentives and Biodiversity Conservation in the United States*, 11 J. Envtl. L. & Litig. 9 (1996); Duangjai Intarapravich & Allen L. Clark, *Performance Guarantee Schemes in the Minerals Industry for Sustainable Development*, 20 RESOURCES POL'Y 59 (1994); Douglas A. McWilliams, *Environmental Justice and Industrial Redevelopment: Economics and Equality in Urban Revitalization*, 21 ECOL. L. Q. 705 (1994); Robert Costanza & Laura Cornwell, *The 4P Approach to Dealing with Scientific Uncertainty*, ENV'T, at 12, Nov. 1992; Robert Costanza & Charles Perrings, *A Flexible Assurance Bonding System for Improved Environmental Management*, 2 ECOL. ECON. 57 (1990); Barbara S. Webber & David J. Webber, *Promoting Economic Incentives for Environmental Protection in the Surface Mining Control and Reclamation Act of 1977: An Analysis of the Design and Implementation of Reclamation Performance Bonds*, 25 NAT. RESOURCES J. 389 (1985). Some discussion has also been given to assurance bonding in the context of wetlands mitigation banks, although the role played by the bonds in that context is somewhat distinctive. *See* Jennifer L. Bolger, *Creating Economic Incentives to Preserve Unique Ecosystems: Should Wisconsin Adopt a Private Wetlands Mitigation Banking Policy?*, 83 Marq. L. Rev. 625 (2000); *Federal Guidance for the Establishment, Use and Operation of Mitigation Banks*, 60 Fed. Reg. 58605, 58613 (Nov. 28, 1995). Finally, one paper has suggested the use of bonds that are convertible into corporate stock as a compliance incentive mechanism. *See* André Schmitt & Sandrine Spaeter, *Improving the Prevention of Environmental Risks with Convertible Bonds*, 50 J. ENVTL. ECON. & MGMT. 637 (2005).

proof on private actors seeking to introduce new substances or technologies, to alter existing land uses, or to otherwise interfere with the dynamism and complexity of the environment. Like the asymmetric humility of their opponents, however, supporters of the PP arguably downplay the severity and significance of these same traits when it comes to sociolegal systems, ignoring problems associated with regulation such as unintended consequences, compensating behaviors, and agency capture.

The environmental assurance bond tries to steer a middle course between these extremes of asymmetric humility. Unlike typical cost-benefit approaches, environmental assurance bonding acknowledges uncertainty regarding the value, resilience, and replaceability of biophysical systems by assessing serious ex ante financial responsibility for the potential causation of environmental harm. At the same time – and in contrast to strict interpretations of the PP – environmental assurance bonding acknowledges the strength and dynamism of sociolegal systems such as markets by allowing private actors to proceed with potentially beneficial activities despite the existence of a credible risk of harm. Indeed, environmental assurance bonding actively marshals the decentralized decisionmaking power of markets as a force for the development of knowledge regarding uncertain substances and activities. As such, the policy approach reflects a high degree of what might be called *ecological rationality*, approaching ill-posed regulatory problems with a pragmatic combination of respect for the power of markets and human technology, and caution before the complexities of nature.[15] Critically, previous academic discussions of environmental assurance bonds have tended to understate the epistemic challenge facing regulators. They have approached the pros and cons of environmental assurance bonds from an efficiency-

[15] As note *infra* text accompanying notes __-__, cognitive psychologists have coined the term *ecological rationality* to refer to choice and judgment heuristics that are well-adapted to real-world decisionmaking environments in which optimific approaches, such as CBA or formal axiomatic systems, founder.

oriented perspective in which the "optimal" level of safety incentive can in principle be identified and applied to private actors, rather than from a more dynamic institutional perspective in which a substantial aim of the regulatory project is to influence *how we come to know what we will come to know*. Indeed, the feature of environmental assurance bonding that commentators tend most to critique – the requirement that financial assurance obligations be set at a level equal to the worst-case outcome threatened by the regulated activity – in fact represents the very heart of the approach's pragmatic wisdom. Recognizing that for many regulatory issues the "right" or "optimal" level of safety incentive cannot *in principle* be identified, supporters of environmental assurance bonding instead utilize the worst-case outcome approach precisely in order to incentivize the development of greater understanding regarding the regulated activity's potential consequences.

This Article is organized as follows. Part I draws on complexity theory to describe the regulatory landscape, both as it pertains to biophysical systems such as aquatic environments and sociolegal systems such as product markets. As Part I describes, differences in ontological outlook tend to drive differences in scientific agenda: While classically-oriented scientists hope to achieve *convergence* at the nanoscale by fusing nanotechnology, biotechnology, information technology, and cognitive science into a single, unified and comprehensive scientific field,[16] ecologists, conservation biologists, and other observers of complex adaptive systems emphasize the ineliminable phenomenon of *emergence*, whereby certain system properties appear at the macroscale in a manner that simply cannot be predicted or explained through an examination of constituent system components alone. Part II argues that the former approach tends to instill technological optimism and a conviction that human ingenuity and progress generally can overcome any impediments and

[16] *See* http://www.infocastinc.com/nbic/nbichome.htm.

scarcities posed by the natural world. The latter approach, in contrast, tends to counsel humility and caution in the face of inevitable – and often unpleasant – ecological surprise. Part II further uses teachings of decision theory and cognitive psychology to reveal complementary inadequacies in the policymaking approaches that are epitomized by CBA and the PP. Finally, in light of these complementary inadequacies, Part III argues that participants in the risk regulation debate should offer their support for policy tools, such as environmental assurance bonds, that give due respect to the most critical aspects of both CBA and the PP. Reduced to a slogan, ecological rationality demands symmetric humility.

I. UNCERTAINTY AND COMPLEXITY IN THE ENVIRONMENT

Managing the risks of a nascent field such as nanoscale science and engineering is a perplexing task, characterized by great uncertainty and likelihood of tradeoffs. For instance, the same properties that make nanomaterials attractive as industrial inputs – namely, their increased reactivity and often dramatically altered optical, electrical, and magnetic behavior compared to macroscale counterparts – also make their toxicity and environmental fate difficult to predict and assess. For instance, given their miniscule size, nanomaterials may penetrate cells more easily than larger materials, a feature that makes them attractive as potential drug delivery devices, but that also raises concerns about their potential adverse health effects.[17] Similarly, although scientists expect to achieve a host of breakthroughs in electrical and mechanical engineering by using highly conductive carbon nanotubes which are as strong as steel but which remain remarkably light and flexible, regulators increasingly are expressing concern that such tubes seem also to share many of the physical and

[17] *See* The Royal Society and The Royal Academy of Engineering, *supra* note __, at ix. *See id.* at __.

toxicological characteristics of asbestos fibers.[18] Because an important feature of nanoparticles is their comparatively large surface area to mass ratio, some scientists also believe that they may be significantly more toxic per unit of mass than larger particles of the same chemical.[19] Indeed, some scientists maintain that the nanoscale itself may entail toxic characteristics, irrespective of the particular chemical makeup of any nanomaterial that is confronted by a human subject.[20]

Although the number of studies addressing potential adverse health and environmental effects of nanomaterials has increased significantly in recent years as governments have begun to direct a larger share of public research support to such questions, the area remains riddled with uncertainty.[21] Yet, stark though it may be, this epistemic vacuum hardly distinguishes nanotechnology from other subjects of environmental, health, and safety regulation. Indeed, a long recognized hallmark feature of such regulation has been the informational and cognitive limitations that face any regulator's ability to identify, understand, and predict the consequences of risk-creating activities, including the act of regulation itself.[22] Accordingly, a critical challenge for risk regulation is to ensure that the regulator's decisionmaking models are appropriately suited to the nature

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[18] *See* Katharine Sanderson, *Migrating Nanotubes Add to Asbestos Concern*, Nature News doi:10.1038/news.2009.217 (March 31, 2009), available at http://www.nature.com/news/2009/090331/full/news.2009/217.html; C.A. Poland et al., 3 Nature Nanotech 423 (2008).

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[21] For instance, a British scientific report noted in 20__ that "[t]here is virtually no information available about the effect of nanoparticles on species other than humans or about how they behave in the air, water or soil, or about their ability to accumulate in food chains." *Id.* at x.

[22] *See* Daniel C. Esty, *Environmental Protection in the Information Age*, 79 N.Y.U. L. REV. 115, 124 (2003) (noting that "pervasive uncertainties are simply assumed by most scholars to be part of the framework within which environmental law must operate"). Esty believes that developments in information technology and other scientific fields will significantly reduce environmental uncertainty and increase the likelihood of regulatory efficacy. As noted *infra* text accompanying notes __-__, however, some degree of uncertainty is likely to plague environmental decisionmaking irrespective of scientific progress, given the nature of complex adaptive systems.

and degree of uncertainty faced, whether the models concern the assessment of ecological or human health hazards, the calculation of economic costs, or some more ambitious integration of the two.

Biophysical Systems. As J.B. Ruhl has observed, advances in ecological science have made a "mess" of thinking about environmental law and policy.[23] The romantic notion that nature can be preserved in a stable equilibrium untouched by human influence has long since been discredited, not merely by improved theoretical understanding of the inherent dynamism and disorder of ecosystems,[24] but also by increasing awareness of the fundamental interconnectedness between ecosystems and *other* complex adaptive systems, including especially those that are associated with human activity.[25] To take only the most vivid example, greenhouse gases emitted through fossil fuel combustion, deforestation, and other human activities have contributed to climatic changes that are occurring on a planetary scale, with potential consequences for all life forms in all areas of the globe.[26] Moreover, as demonstrated by the fact that existing anthropogenic greenhouse gas emissions will continue to affect the atmosphere for decades or even centuries beyond the present one, the desire simply to "let nature be" no longer generates meaningful guidance for environmental policymaking. Instead, as Ruhl recently put it, "[t]he reality is that there simply is no way to

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[23] *Cf.* J.B. Ruhl, *Thinking of Environmental Law as a Complex Adaptive System: How to Clean up the Environment by Making a Mess of Environmental Law*, 34 HOUS. L. REV. 933 (1997).

[24] *See* Jonathan Baert Wiener, *Beyond the Balance of Nature*, 7 DUKE ENVTL. L. & POL'Y F. 1 (1996); A. Dan Tarlock, *The Nonequilibrium Paradigm in Ecology and the Partial Unraveling of Environmental Law*, 27 LOY. L.A. L. REV. 1121 (1994); Fred Bosselman & A. Dan Tarlock, *The Influence of Ecological Science on American Law: An Introduction*, 69 CHI.-KENT L. REV. 847, 869-879 (1994).

[25] DANIEL BOTKIN, DISCORDANT HARMONIES: A NEW ECOLOGY FOR THE TWENTY-FIRST CENTURY 188 (1990) (observing that "life and environment are one thing, not two, and people, as all life, are immersed in the one system").

[26] The spread of invasive species represents a human-influenced problem of similarly global proportions. *See generally* HARMFUL INVASIVE SPECIES: LEGAL RESPONSES (Marc Miller & Robert Fabian, eds., 2004).

'preserve' nature without in some sense managing it somewhere with some kind of human-defined purpose."[27]

In response to these developments, the concept of "ecosystem management"[28] has arisen with a goal of "integrat[ing] scientific knowledge of ecological relationships within a complex sociopolitical and values framework toward the general goal of protecting native ecosystem integrity over the long term."[29] As conservation biologists and others have emphasized, the long-run integrity of ecosystems is important not merely because non-human life forms within those systems may have some intrinsic value by virtue of their existence alone, but also because humanity depends in numerous ways on the "ecosystem services" that are provided by well-functioning ecosystems and the shifting web of life forms that comprise them.[30] Conversely, ecosystem functioning is affected in a multitude of ways by the behavior of humans, whose macroscale policies and microscale decisions contribute to a state of irrevocable interdependence between social and ecological systems.

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[27] J.B. Ruhl, *The Myth of What is Inevitable Under Ecosystem Management: A Response to Pardy*, 21 PACE ENVTL. L. REV. 315 (2004).

[28] *See* JOHN COPELAND NAGLE & J.B. RUHL, THE LAW OF BIODIVERSITY AND ECOSYSTEM MANAGEMENT (2002). Ecosystem management relates closely to C.S. Holling's notion of "adaptive management," from which the newer field derives its basic management principle of continuous monitoring and adjustment. *See* ADAPTIVE ENVIRONMENTAL ASSESSMENT AND MANAGEMENT (C.S. Holling ed., 1978). *See also* KAI N. LEE, COMPASS AND GYROSCOPE 53 (1993) (describing adaptive management as an application of "the concept of experimentation to the design and implementation of natural-resource and environmental policies").

[29] R. Edward Grumbine, *What is Ecosystem Management?*, 8 CONSERVATION BIOLOGY 27, 31 (1994). *See also* Norman L. Christensen, *The Report of the Ecological Society of America Committee on the Scientific Basis for Ecosystem Management*, 6 ECOLOGICAL APPLICATIONS 665 (1996) (describing ecosystem management as "driven by explicit goals, executed by policies, protocols, and practices, and made adaptable by monitoring and research based on our best understanding of the ecological interactions and processes necessary to sustain ecosystem composition, structure, and function").

[30] *See generally* James Salzman, Barton H. Thompson, Jr., & Gretchen C. Daily, *Protecting Ecosystem Services: Science, Economics, and Law*, 20 STAN. ENVTL. L. REV. 309, 327 (2001); Robert L. Fischman, *The EPA's NEPA Duties and Ecosystem Services*, 20 STAN. ENVTL. L. J. 497 (2001); Barton H. Thompson, Jr., *Markets for Nature*, 25 WM. & MARY ENVTL. L. & POL'Y REV. 261 (2000); GEOFFREY HEAL, NATURE AND THE MARKETPLACE: CAPTURING THE VALUE OF ECOSYSTEM SERVICES (2000); J.B. Ruhl, *Valuing Nature's Services: The Future of Environmental Law?*, 13-SUM NAT. RESOURCES & ENV'T. 359 (1998); James Salzman, *Valuing Ecosystem Services*, 24 ECOLOGY L. Q. 887, 893 (1997); NATURE'S SERVICES: SOCIETAL DEPENDENCE ON NATURAL ECOSYSTEMS (Gretchen Daily, ed., 1997).

Accordingly, proponents of the ecosystem management paradigm view their task as one of identifying, monitoring, and sustaining evolutionary and ecological processes, recognizing that those processes occur within a complex of multiple, interconnected systems, including political, economic, and other sociolegal systems that help to determine the human impact on ecosystems.

Lurking behind the ecosystem management approach is an ontology informed by the teachings of complexity theory. In pithy terms, complexity theory suggests that researchers and regulators should expect the unexpected whenever they examine complex adaptive systems such as immune systems, coral reefs, the global climate, the world economy, or even a pattern as seemingly mundane and uncomplicated as a dripping faucet.[31] Complexity theory should be deliberately contrasted with the reductionist focus of the Newtonian tradition in science, which attempts to understand the world by breaking it down into smaller and smaller components for isolated study. Although clearly fruitful for a variety of tasks, a central tenet of complexity theory is that "the reductionist methodology will never lead to a fully predictive theory of any complex system."[32] For instance, researchers may be able to identify the dose-response curve that characterizes the acute toxicity effects of a given nanomaterial on a given species within the splendor of a controlled laboratory environment, but at the same time they may miss entirely the effects of the substance on the species in its broader ecological context. In order to begin to grasp these more dynamic,

[31] *See* Ruhl, *supra* note __, at 936.

[32] *Id.* at 937 (citing JOHN H. HOLLAND, HIDDEN ORDER (1995); JAMES GLEICK, CHAOS: MAKING A NEW SCIENCE (1987); BRIAN GOODWIN, HOW THE LEOPARD CHANGED ITS SPOTS: THE EVOLUTION OF COMPLEXITY (1996)).

slippery effects, complexity theory suggests that researchers must adopt a different "pre-analytic vision" of the systems that they are attempting to model.[33]

The pre-analytic vision of complex adaptive systems differs in a number of significant ways from the alternative vision of systems that are comprised by linear, independently-operating components. First, complexity theory presupposes that micro-level interactions between numerous forces or agents within a system give rise to patterns of behavior that are only detectable when the system is viewed at the macro-level, in its entirety.[34] The ant or termite colony provides a vivid example, as it exhibits extraordinary features such as temperature regulation and geographic orientation that simply cannot be predicted or accounted for by examining the behavior of individual colony members alone.[35] Second, complex adaptive systems often exhibit nonlinear relationships and behaviors, such that they do not display mathematical proportionality in the tidy manner assumed by classical science and mathematics.[36] This is not to suggest that the systems are indeterminate, but rather that their rules of operation give rise to stunningly complex and difficult-to-predict interactions. Extremely minor, even immeasurable variations in conditions between two otherwise identically situated systems – such as the presence in one system of the proverbial

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[33] As is well recognized by philosophers of science, the choice of pre-analytic vision affects fundamentally the nature of the questions that researchers ask and the empirical evidence that they seek. *See* Douglas A. Kysar, *Law, Environment, and Vision*, 97 NORTHWESTERN UNIV. L. REV. 675 (2003) ("[A]nalytic effort is of necessity preceded by a preanalytic cognitive act that supplies the raw material for the analytic effort . . . . [T]his preanalytic cognitive act will be called Vision.") (quoting JOSEPH A. SCHUMPETER, HISTORY OF ECONOMIC ANALYSIS 41 (1954)).

[34] *See* PETER COVENEY & ROGER HIGHFIELD, FRONTIERS OF COMPLEXITY: THE SEARCH FOR ORDER IN A CHAOTIC WORLD 7 (1995).

[35] To wit, cylindrical termite mounds found in Northern Australia – constructed and maintained by hundreds of thousands of short-lived, sterile worker members – can stretch to 8 meters tall and survive as long as 100 years. The mounds face consistently in a north-south direction such that the sun warms the structure during the morning and evening, while only a thin edge is exposed to the heat of the sun during the day. Worker termites help to further regulate temperature by opening and closing ventilation chambers, by clustering for warmth, and by excavating for cool water droplets, such that the mound system in the aggregate is able to maintain its core temperature with remarkable precision year-round. *See* J. SCOTT TURNER, THE EXTENDED ORGANISM: THE PHYSIOLOGY OF ANIMAL-BUILT STRUCTURES (2000).

[36] *See* Ruhl, *supra* note __, at 946-947.

flapping of a butterfly's wings[37] – can give rise to dramatic differences in outcome between the two systems only a few evolutionary steps later. The resulting "chaos" is not randomness per se, but rather "order masquerading as randomness,"[38] a state of being that, although deterministic, nevertheless remains irreducibly uncertain.

Third, in addition to sensitivity to minor variations in conditions, complex systems also are characterized by feedback and feedforward loops, in which system components influence other components that, in turn, cause their own effects on the original, as well as many other, components within the system.[39] Cause and effect pathways, in other words, are not terminal and unidirectional. Instead, the components of a system are interconnected through numerous multidirectional paths of relation and dependence.[40] This state of interconnection often leads to multiplier effects and other self-reinforcing tendencies that render a system's condition at any given time path dependent and, therefore, not easily reversed or altered.[41] For example, if researchers discover that release of a nonparticle into a particular habitat destroys zooplankton and leads to a proliferation of algae, which in turn promotes the expansion of a particular amphibian species, it will be impossible for even the most skilled ecosystem manager to restore the original "equilibrium" that once characterized

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[37] *See* GLEICK, *supra* note __, at 20-23.

[38] *Id.* at 22.

[39] *See id.* at 947-948.

[40] For instance, one classic example of ripple effects from ecology concerned a decline in the availability of forage fish near Alaska's Aleutian archipelago, which caused a decrease in the population of seals and sea lions (a dietary staple of killer whales), which caused killer whales to shift their diet to sea otters, which caused an increase in the population of sea urchins (a dietary staple of sea otters), which finally in turn caused a sharp decrease in kelp forests (a dietary staple of sea urchins). *See* J. A. Estes et al., *Killer Whale Predation on Sea Otters Linking Oceanic and Nearshore Ecosystems*, 282 SCI. 473 (1998)

[41] *See* Oona Hathaway, *Path Dependence in the Law: The Course and Pattern of Legal Change in a Common Law System*, 86 IOWA L. REV. 601, 606-622 (2001) (surveying variations of path dependence theory).

the habitat. Instead, the system will only be able to continue adapting in some manner or another from its present, path-dependent state.[42]

Finally, an important consequence of these various features of complex adaptive systems is that normal or Gaussian probability theory may be highly misleading when used to predict or describe their behavior. As Farber has discussed, "[c]omplex systems . . . are often characterized by a different kind of statistical distribution called a 'power law.'"[43] Systems that are subject to power laws display a number of peculiar features. Most notably, they typically have "fat tails,"[44] in which large or even extreme events appear with a regularity that would be unthinkable from the perspective of normal probability assumptions. Indeed, as Farber notes, "it is possible for a variable subject to a power law to have an infinite variance or even an infinite expected value."[45] In light of their fat tails, large or infinite variances, and other non-Gaussian features, systems governed by power laws are not adequately described by conventional statistical concepts such as the mean or the mode. Indeed, by focusing only on average outcomes in the conventional manner, analysts of complex adaptive systems risk ignoring important – even potentially catastrophic – aspects of the system's behavior. Their mistake, in essence, is to apply a pre-analytic vision of order to a system of chaos. As two pioneering thinkers in the ecosystem management field have written, "in no place can we claim to predict with certainty either the ecological effects of the activities, or the efficacy of most measures aimed at regulating or enhancing them. Every major change in harvesting rates and management practices is in fact a perturbation

[42] Hence, the new paradigm of "non-equilibrium ecology." *See* Bosselman & Tarlock, *supra* note __, at __.

[43] Farber, *supra* note __, at 146-147.

[44] *Id.* at 155.

[45] *Id.*

experiment with highly uncertain outcome, no matter how skillful the management agency is in marshalling evidence and arguments in support of the change."[46]

Sociolegal Systems. The process of Darwinian evolution has long provided the leading metaphorical explanation for the operation of economic markets.[47] Naturally, then, as our vision of biophysical systems and evolutionary processes sharpens to include complexity and dynamism as foundational characteristics, so too might our understanding of market operations evolve to embrace such characteristics. Recently, a number of theorists have begun to mine the field of complexity theory for insight into economics in precisely this manner.[48] Their findings include nonlinear discontinuities in price dynamics, extreme sensitivity over time to minor variations in conditions, powerful feedback loops that contribute to bubbles and other extreme economic events, and many other hallmark features of complex adaptive systems. Mathematician Benoit Mandlebrot, an important intellectual figure in the development of fractal geometry and complexity theory, expects these initial findings to lead in time to nothing short of a revolution in the theory of economics and finance. He argues that, at bottom, "[t]he geometry that describes the shape of coastlines and the patterns of galaxies also elucidates how stock prices soar and plummet."[49]

It is too early to tell whether Mandlebrot's vision of a revolutionized economic theory will come to fruition, although the global economic collapse that began in late 2009

[46] C. Walters & C.S. Holling, Large-Scale Management Experiments and Learning By Doing, 71 Ecology 2060 (1990).

[47] *See* Mark J. Roe, *Chaos and Evolution in Law and Economics*, 109 HARV. L. REV. 641, 642 (1996) (referring to the "paradigm of a Darwinian survival of the fittest in law and economics").

[48] *See* BENOIT MANDELBROT & RICHARD L. HUDSON, THE (MIS)BEHAVIOR OF MARKETS (2004); EDGAR E. PETERS, CHAOS AND ORDER IN THE CAPITAL MARKETS : A NEW VIEW OF CYCLES, PRICES, AND MARKET VOLATILITY (1996); EDGAR E. PETERS, FRACTAL MARKET ANALYSIS: APPLYING CHAOS THEORY TO INVESTMENT AND ECONOMICC (1994); J. Barkley Rosser, Jr., *On the Complexities of Complex Economic Dynamics*, 13 J. ECON. PERSP. 169 (Fall 1999); Roe, *supra* note __.

[49] Benoit B. Mandelbrot, *A Multifractal Walk Down Wall Street*, SCI. AM., February, 1999.

has certainly strengthened the case for inclusion of greater systemic analysis of market behavior and greater levels of humility regarding the power of positivistic financial modeling. Even before those events, however, one already could identify traces of complexity theory in much of prevailing thought about markets and regulation. An important theme of the risk reform debate, for instance, has been repeated emphasis on the possibility of "unintended consequences" from regulation.[50] Just as ecosystems are believed to be characterized by pronounced and often unpredictable changes due to minor perturbations, markets are said to exhibit "substitution effects,"[51] "compensating behaviors,"[52] and a host of other unanticipated results that flow from government regulatory interventions. For instance, in one classic example, economist Sam Peltzman argues that highway safety regulations such as mandatory seatbelt laws may lead drivers to reduce their own level of caution, generating an accident rate that is higher overall than without the regulation.[53] Similarly, Kip Viscusi contends that child-proof container requirements for medicines may give parents a false

[50] For a critical overview, see Mark Kelman, *On Democracy-Bashing: A Skeptical Look at the Theoretical and "Empirical" Practice of the Public Choice Movement*, 74 VA. L. REV. 199 (1988).

[51] *See* Samuel J. Rascoff & Richard L. Revesz, *The Biases of Risk Tradeoff Analysis: Towards Parity in Environmental, Health, and Safety Regulation*, 69 U. CHI. L. REV. 1763, 1775 (2002) ("Sometimes a regulation will bring about a risk tradeoff when it effects a shift from one product or process to another, which in turn gives rise to risks of its own.").

[52] *See* Peter A. Veytsman, *Drug Testing Student Athletes and Fourth Amendment Privacy: The Legal Aftermath of* Veronica v. Action, 73 TEMPLE L. REV. 295, 325 (2000) (referring to "the theory of compensating behavior, in which people's responses to government regulations are often contrary to the intended effect of the regulation"). *See also* BJORN LOMBORG, THE SKEPTICAL ENVIRONMENTALIST: MEASURING THE REAL STATE OF THE WORLD 10 (2001) (arguing that "scrapping pesticides would actually result in more cases of cancer because fruits and vegetables help to prevent cancer, and without pesticides fruits and vegetables would get more expensive, so that people would eat less of them"); William N. Evans & Matthew C. Farrelly, *The Compensating Behavior of Smokers: Taxes, Tar, and Nicotine*, 29 RAND J. ECON. 578 (1998) (concluding that higher cigarette taxes may lead some smokers to consume higher tar and higher nicotine cigarettes, thereby counteracting the health benefits that governments hoped to achieve from lower consumer demand attributable to the higher product price).

[53] *See* Sam Peltzman, *The Regulation of Auto Safety*, in AUTO SAFETY REGULATION: THE CURE OR THE PROBLEM? 2-3 (Henry G. Manne & Roger LeRoy Miller eds., 1976).

sense of security, prompting them to leave drugs within reach of children and leading ultimately to more children at risk than before the requirements were imposed.[54]

This "law of unintended consequences"[55] also find expression within the context of environmental regulation, where commentators often cite failed attempts by government officials to limit fishery harvesting as a particularly telling example. Jonathan Adler provides a succinct summary of this tragicomical tale:

> It is now generally accepted that traditional regulatory approaches to fishery conservation have been a spectacular failure. Regulatory controls have typically taken the form of limits on fishing seasons, boat size, fishing areas, equipment and the like. . . . However well-intentioned, such rules often lead to absurd results. License controls and other entry restrictions may limit the number of fishers, but they do not control the amount or intensity of fishing efforts. Mandates on the type of equipment that can be used, an effort to control total catch by mandating that fishers use less-efficient means of catching fish, encourage fishers to increase their investment in additional vessels or gear to compensate for the efficiency losses. Limits on the number of days fished encourage fishers to increase their effort on those days allowed. The results are rampant overcapitalization in fisheries and a destructive "derby" system in which each fisher races to catch as much as he or she can before the season closes.[56]

In short, the regulator's attempt to manage fishery harvesting levels through governmental controls is thwarted at each stage by unanticipated counter-adjustments and other reactive processes within the commercial fishing market. The lesson of the tale is familiar: The regulator assumes linearity and predictability when, in fact, the system being regulated is complex.

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[54] *See* W. KIP VISCUSI, FATAL TRADEOFFS: PUBLIC AND PRIVATE RESPONSIBILITIES FOR RISK 234-242 (1992). Viscusi refers more broadly to a "lulling effect," whereby the introduction of government safety regulations "produce[s] misperceptions that lead consumers to reduce their safety precautions because they overestimate the product's safety." *Id.* at 225. *See also* W. Kip Viscusi, *Consumer Behavior and the Safety Effects of Product Safety Regulations*, 28 J.L. & ECON. 527, 537-46 (1985).

[55] *See* Jon D. Hanson & David Yosifon, *The Situation: An Introduction to the Situational Character, Critical Realism, Power Economics, and Deep Capture*, 152 U. PA. L. REV. 129, 227 (2003) (noting that "the law of unintended consequences" often is invoked to suggest that "imperfect markets might be preferable to imperfect regulations").

[56] Jonathan H. Adler, *Legal Obstacles to Private Ordering in Marine Fisheries*, 8 ROGER WILLIAM UNIV. L. REV. 9, 15 (2002) (internal citations and quotation marks omitted).

Compensating behaviors are but one way in which government risk regulations are thought to entail subtle, but significant secondary effects. Other claimed "risk tradeoffs"[57] of environmental, health, and safety regulation include direct or "iatrogenic" effects such as the possibility that "cleaning up Superfund sites, or removing asbestos from buildings, may put workers at risk of exposure and occupational injury"[58]; and "health-health tradeoffs" such as the increased mortality and morbidity that is said to flow merely from the act of expending money on regulatory compliance.[59] In light of these various tradeoffs, scholars have advocated "risk-risk analysis"[60] as a mechanism for focusing decisionmakers on *all* of the negative effects that may be expected to come from adopting a particular environmental, health, or safety standard. Such comprehensive risk analysis is thought to be desirable because the adaptive behaviors and activities of market participants evade casual prediction:

[57] John D. Graham & Jonathan Baert Wiener, *Confronting Risk Tradeoffs*, in RISK V. RISK: TRADEOFFS IN PROTECTING HEALTH AND THE ENVIRONMENT 1 (John D. Graham & Jonathan Baert Wiener, eds., 1995).

[58] Jonathan Baert Weiner, *Managing the Iatrogenic Risks of Risk Management*, 9 RISK: HEALTH, SAFETY, & ENV. 39, 40 (1998). According to Weiner, such "countervailing risks" caused or increased by regulation are "ubiquitous." *Id.*

[59] The argument is not as specious as it initially sounds. Proponents of health-health analysis cite the consistent and significant correlation that has been found between individual and family income and health, particularly as measured by longevity. *See, e.g.,* W. Kip Viscusi, *Regulating the Regulators*, 63 U. CHI. L. REV. 1423, 1452-1453 (1996); Randall Lutter & John F. Morrall III, *Health-Health Analysis: A New Way to Evaluate Health and Safety Regulation*, 8 J. RISK & UNCERTAINTY 1, 44 (1993) ("Health-health analysis seeks to quantify the expected declines in health and safety that may be ascribed to the costs of complying with a regulation."); *see also* Randall Lutter, John Morrall, & W. Kip Viscusi, *The Cost-Per-Life-Saved Cutoff for Safety-Enhancing Regulations*, 37 ECON. INQ. 599 (1999); Frank B. Cross, *When Environmental Regulations Kill: The Role of Health/Health Analysis*, 22 ECOL. L.Q. 729 (1995); Ralph L. Keeney, *Mortality Risks Induced by the Costs of Regulations*, 8 J. RISK & UNCERT. 95 (1994); W. Kip Viscusi & Richard J. Zeckhauser, *The Fatality and Injury Costs of Expenditures*, 8 J. RISK & UNCERT. 19 (1994). In light of this correlation, supporters argue that *any* regulation will entail adverse health consequences, so long as compliance with the regulation requires a reduction in income: "regulatory expenditures represent opportunity costs to society that divert resources from other uses. These funds could have provided for greater healthcare, food, housing, and other goods and services that promote individual longevity." *Id.* at 1452. Even supporters of health-health analysis, however, acknowledge that the identified statistical correlation between income and health is far from a demonstration of causation. *See id.* at 1455. Accordingly, the argument linking regulatory expenditures with reduced health depends at its core upon little more than faith in a series of counterfactual assumptions about the opportunity costs of regulation.

[60] *See, e.g.,* Jonathan B. Wiener, *Precaution in a Multi-Risk World*, in HUMAN AND ECOLOGICAL RISK ASSESSMENT: THEORY AND PRACTICE 1509 (Dennis D. Paustenbach ed., 2002); MARGOLIS, *supra* note __; Cass R. Sunstein, *Health-Health Tradeoffs*, 63 U. CHI. L. REV. 1533 (1996); Symposium, *Risk-Risk Analysis*, 8 J. RISK & UNCERTAINTY 5 (1994); AARON WILDAVSKY, SEARCHING FOR SAFETY 212 (1988); Chauncey Starr & Christopher Whipple, *Risks of Risk Decisions*, 208 SCI. 1114 (1980). Unlike many other writers in the risk-risk analysis field, Wiener is careful to distinguish the so-called "wealthier is healthier" effect from other "countervailing risks" of regulation. *See* Wiener, *supra* note __, at 53.

As the story of hapless fishery management indicates, failure to rigorously cast about in search of unintended consequences before acting may lead regulators to govern ineffectively or, indeed, to cause harm where they intend good.

To date, critics of risk regulation have successfully highlighted the notion that government actions within market environments may cause unanticipated effects that work at cross purposes with the goal of government action. Less well appreciated, however, has been the fact that regulations also can entail unintended consequences that are beneficial.[61] Researchers studying climate change mitigation policies, for instance, have calculated that the "ancillary benefits" of greenhouse gas mitigation – such as the incidental reduction of other harmful air pollutants (e.g., sulfur dioxide, nitrogen oxides, volatile organic compounds, and particulates) – may be as high as $20 per ton of emissions reduced in 1990 U.S. dollars, an amount that is comparable in magnitude to estimates of the direct benefits of climate change policies.[62] As Samuel Rascoff and Richard Revesz have argued, similar "ancillary benefits have been observed across a broad range of contexts."[63] Because the debate over regulatory reform has tended to ignore this reality, however, "[t]he resulting legal and scholarly conclusions about the desirability of regulation [have been] consistently distorted."[64]

The overlooked phenomenon of ancillary benefits suggests that the interaction between government regulation and markets is more complex than even members of the unintended consequences school tend to appreciate. To complicate matters still further, once the analyst decides to include substitution effects or other endogenous behavioral

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61 *See* Rascoff & Revesz, *supra* note __, at 1791 ("Advocates of risk tradeoff analysis, while aspiring to a more 'holistic' approach to regulation, consistently ignore the possibility that regulatory interventions will produce ancillary benefits and not merely ancillary harms.").

62 *See* Douglas A. Kysar, *Some Realism About Environmental Skepticism: The Implications of Bjorn Lomborg's The Skeptical Environmentalist for Environmental Law and Policy*, 30 ECOLOGY L. Q. 223, __ (2003).

63 Rascoff & Revesz, *supra* note __, at 1766.

64 *Id. See also* Richard Revesz & Michael Livermore, Retaking Rationality.

responses to regulation, then it is not a large theoretical step to admit that endogenous shifts may also occur with respect to preferences.[65] Contrary to the standard assumption of many schools of policy analysis, markets and other sociolegal systems are not characterized by linear, unidirectional relationships between public values and the law, on the one hand, and the law and its subjects, on the other. Rather, the system of relationships among these forces exhibits feedback loops, oscillations, and other characteristic traits of complex adaptive systems, including a state of reciprocal influence between the law and public values. Thus, just as legal policies may affect behavior in complex and unanticipated ways, so too may policies alter the beliefs and attitudes of individuals, including perhaps the very beliefs and attitudes that initially justify a policy choice. As Cass Sunstein has noted, these "preference-shaping effects of legal rules cast doubt on the idea that . . . regulation should attempt to satisfy or follow some aggregation of private preferences . . . . When preferences are a function of legal rules, the rules cannot be justified by reference to the preferences."[66]

Unintended consequences, ancillary benefits, and endogenous preferences all reflect an important truism identified nearly one half century ago by two economists in a classic

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[65] *See, e.g.,* Cass R. Sunstein, *Endogenous Preferences, Environmental Law*, 22 J. LEGAL STUD. 217 (1993).

[66] *Id.* at 234-235. *See also* Richard H. Thaler & Cass R. Sunstein, *Libertarian Paternalism*, 93 AM. ECON. REV. 175, 178 (2003) (noting that "[w]hat people choose often depends on the starting point, and hence the starting point cannot be selected by asking what people choose," and that, at times, this "problem of circularity dooms the market-mimicking approach"); CASS R. SUNSTEIN, FREE MARKET AND SOCIAL JUSTICE 17 (1997) ("[W]hen preferences are a function of legal rules, the government cannot take preferences as given [and] the rules cannot be justified by reference to the preferences . . . ."). *Cf.* Samuel Bowles, *Endogenous Preferences: The Cultural Consequences of Markets and other Economic Institutions*, 36 J. ECON. LIT. 75, 75 (1998) (describing conceptual problems created for economic theory when markets "influence the evolution of values, tastes, and personalities").

Still further complications arise from the fact that government rules, regulations, and requirements may themselves interact and behave as a complex adaptive system, a point that J. B. Ruhl has urged in several articles. *See* J.B. Ruhl & James Salzman, *Mozart and the Red Queen: The Problem of Regulatory Accretion in the Administrative State*, 91 GEO. L. J. 757 (2003); Ruhl, *supra* note __; J.B. Ruhl, *Complexity Theory as a Paradigm for the Dynamical Law-and-Society System: A Wake-Up Call for Legal Reductionism and the Modern Administrative State*, 45 DUKE L. J. 849 (1996); J.B. Ruhl & Harold J. Ruhl, Jr., *The Arrow of the Law in Modern Administrative States: Using Complexity Theory to Reveal the Diminishing Returns and Increasing Risks the Burgeoning of Law Poses to Society*, 30 U.C. DAVIS L. REV. 405 (1997). *See also* Gerald Andrews Emison, *The Potential for Unconventional Progress: Complex Adaptive Systems and Environmental Quality Policy*, 7 DUKE ENVTL. L. & POL'Y F. 167, 192 (1996).

article entitled "The General Theory of the Second Best."[67] In this article, the theorists formally demonstrated that the alleviation of one distortion among many in a given market may not necessarily lead to an overall increase in the efficiency of the market. For instance, at any given time, a particular microeconomic inefficiency may be serving to counteract the effects of another inefficiency such that, if the former were eliminated, society would become worse off in the aggregate, not better. Stated more precisely, "if one or more members of a set of optimal conditions cannot be fulfilled, there is no general reason to believe that fulfilling (or more closely approximating) more of the remaining conditions will bring [society] closer to the optimum than fulfilling fewer of the remaining conditions."[68] The macroeconomic efficiency problem, in that sense, is ill-posed: Many of its determining variables and rules of interrelationship are simply unknown, such that the impact that one or more microeconomic adjustments will have on the system as a whole remains shrouded in deep uncertainty.

Although not expressly premised on complexity theory, the General Theory of the Second Best shares much of that theory's pre-analytic vision. The Theory notes at its heart that the factors determining a macroeconomic equilibrium are so numerous, multifaceted, and interdependent that one simply cannot know whether a microeconomic efficiency improvement will lead, on net, to an improvement at the macroeconomic scale, unless one assumes – contrary to all available evidence – that the microeconomic inefficiency under investigation is the only such inefficiency in the entire system.[69] Participants in the risk

[67] *See* R.G. Lipsey & Kelvin Lancaster, *The General Theory of the Second Best*, 24 REV. ECON. STUD. 11 (1956).

[68] Richard S. Markovits, *Second Best Theory and Law and Economics: An Introduction*, 73 Chi.-Kent L. Rev. 3, 3 (1998).

[69] Thus, as Duncan Kennedy put it, "[t]here is no reason to believe that summing a series of valid partial equilibrium exercises will yield a valid general equilibrium solution." Duncan Kennedy, *The Role of Law in Economic Thought: Articles on the Fetishism of Commodities*, 34 AM. UNIV. L. REV. 939, 963 (1985).

regulation debate exhibit some sensitivity to this complexity by examining policy proposals with an awareness that market inefficiencies other than the target of the proposal may exist and may impact the outcomes of government intervention. For instance, analysts forego the unrealistic assumption that users of child-proof medicine containers are perfectly rational, and instead investigate empirically supported cognitive tendencies that lead them to predict a counterintuitive, and counterproductive, parental response. Similarly, rather than assume an absence of additional pollution externalities when evaluating the costs and benefits of climate change policies, analysts instead examine the actual evidence and discover that a host of harmful air pollution effects currently exist that serendipitously would be alleviated by climate change mitigation. In both cases, by attempting to model the welfare consequences of regulation in a highly interactive – and imperfect – world, the policy analyst demonstrates at least partial awareness of the complexity of sociolegal systems.

II. Uncertainty and Complexity in the Mind

In addition to the external environments they aim to influence, risk regulators also must grapple with problems of uncertainty and complexity within the mind itself, as even well-behaved, well-understood systems will confound the regulator whose judgment is influenced by psychological tendencies that conflict with the realization of a regulatory goal.[70] Within cognitive psychology, a theoretical debate has raged for the last two decades over whether and when heuristic decisionmaking approaches provide superior results to more analytically formalized procedures.[71] Psychologists participating in what has been called the heuristics research tradition claim that individuals often are wise to ignore

[70] *See* Jeffrey J. Rachlinski & Cynthia R. Farina, *Cognitive Psychology and Optimal Government Design*, 87 CORNELL L. REV. 549 (2002).

[71] Phillip Tetlock, & B. Mellers, *The Great Rationality Debate*, 13 PSYCH. SCI. 94 (2002).

available, relevant information and to eschew purposeful attempts to calculate an optimal result in their personal judgment and decisionmaking.[72] According to these theorists, relying instead on heuristic techniques that exploit informational cues and other features of the decisionmaking environment can conserve scarce computational effort while achieving a performance level that approaches the results of deliberate optimization techniques. Moreover, they argue that, in many instances, heuristics provide the only "ecologically rational" manner in which to solve problems given that many, if not most, real world problems are not posed in a manner that permits the identification of an optimal solution, let alone its attainment.[73]

In contrast to these psychologists, the heuristics and biases research program pioneered by Daniel Kahneman and Amos Tversky[74] has become associated with the view that individual decisionmaking heuristics frequently are unreliable and that "corrective" measures such as debiasing efforts or legal interventions are necessary in order to better approximate the ideal of expected utility maximization.[75] Although at times confused and overblown,[76] the contrast between these two viewpoints is nevertheless instructive for the present Article because it parallels in many ways the debate that has taken place between proponents of CBA and supporters of the PP within environmental law and policy. Moreover, in recent years, participants in theoretical debates over the PP and risk regulation

[72] *See* GERD GIGERENZER & PETER TODD, SIMPLE HEURISTICS THAT MAKE US SMART 25-26 (1999) (describing decisionmaking heuristics as "useful, even indispensable cognitive processes for solving problems that cannot be handled by logic and probability theory").

[73] *See id.* at vii (arguing that simple cognitive heuristics persist because "they are ecologically rational, that is, adapted to the structure of the information in the environment in which they are used to make decisions").

[74] *See* Daniel Kahneman & Amos Tversky, *Judgment Under Uncertainty: Heuristics and Biases*, 185 SCI. 1124 (1974) (identifying decisionmaking heuristics as "principles which reduce the complex tasks of assessing probabilities and predicting values to simpler judgmental operations" and which "are quite useful, but sometimes . . . lead to severe and systematic errors").

[75] For leadings statements, see Sunstein; Sunstein & Jolls.

[76] *See* Jeffrey J. Rachlinski, 2005.

more generally have begun to turn to cognitive psychology and behavioural decision theory for insight and support of their policy recommendations. To these theorists, psychological findings offer the potential not only to produce more reliable predictions of behaviour among individuals and other actors that the law is attempting to influence, but also to provide guidance for shaping the content and structure of legal rules themselves, so that they may better resonate with what we know about the human mind.

Rationality in Individual Choice.[77] Within decision theory and cognitive psychology, one tends to encounter both optimality-based and heuristic-based models of how the human mind accesses and processes information. The former category of models encompass fully specified analytic systems in which the processes of decisionmaking are given by formal rules of logic and computation that can be described with mathematical precision, replicated over multiple trials, and extended across diverse tasks. Optimality-based approaches derive generally from rational choice theory and seek to identify the solution or solutions to a problem that are singularly optimal according to a desired criterion, such as expected utility maximization or wealth maximization. Optimization models can be prescriptive, in the sense that they aim to identify the solution that individuals or other decisionmakers should adopt for a given problem, or they can be simply descriptive, in the sense that they aim to predict the choices that decisionmakers will adopt for a given problem. Descriptive models may be further subdivided according to whether they purport to describe the actual processes that decisionmakers utilize in order to solve problems, or whether they instead merely aim to predict the outcomes of decisions, while remaining

[77] This section draws on Douglas A. Kysar et al., *Are Heuristics a Problem or a Solution?*, in HEURISTICS AND THE LAW (Christoph Engel & Gerd Gigerenzer, eds., forthcoming M.I.T. Press, 2005).

agnostic on the particular cognitive processes that individuals employ in order to produce such outcomes.

Heuristics researchers in contrast seek to model and understand directly the cognitive processes that individuals use to make decisions. Such researchers differ, however, in the extent to which they believe that heuristic models supplement, as opposed to supplant, optimization models. The heuristics and biases research program, for instance, has used experimentally observed departures from rational choice theory to glean insights about the mental processes that individuals utilize when evaluating options and making decisions. Accordingly, many view the heuristics and biases program as leading naturally to a "repair model" research agenda, in which heuristics are thought to offer exceptions or additions to the basic theoretical engine of decisionmaking which remains premised fundamentally on expected utility maximization. The heuristics program, on the other hand, seeks to understand decisionmaking from the "bottom up," by identifying and modeling the actual cognitive processes that individuals are believed to use for given decisionmaking tasks and without regard to any basic underlying model of rational choice. Obviously, this level of ambition in the heuristics research agenda carries a likelihood that the program will for some time appear incomplete to theorists who are accustomed to the parsimonious scalability of rational choice theory.

Nevertheless, one important reason that researchers in the heuristics program seek to build a new decisionmaking model from the bottom up stems from their belief that optimization models offer limited applicability to many real world problems. Specifically, in two different manners, decisionmaking problems may be intractable in the sense that no optimal solution can be identified by any presently available optimization model, let alone attained. First, many goals when specified mathematically take the form of "ill-posed" problems; that is, problems that cannot in principle be solved. In this category fall those problems with unknown, vague, or incalculable criteria, and those problems for which an adequate weighting function among criteria cannot be specified. Second, many of the remaining problems that are well-posed are nevertheless computationally intractable. In this category fall those problems that are formally NP-hard – that is, intrinsically harder than the category of problems that can be solved in nondeterministic polynomial time – and those problems that are otherwise practically insoluble given the limits of currently available information technology.

According to researchers in the heuristics tradition, the fact that many problems cannot be solved with traditional optimization-based techniques has both descriptive and prescriptive implications. Descriptively, it raises a further challenge – in addition to the challenge presented by the behavioral findings of the heuristics and biases research program[78] – to the notion that individual judgment and decisionmaking can best be predicted by a model of expected utility maximization. The fact that humans face many problems that do not admit of optimal solutions has made it adaptively desirable over time that humans *not* seek to replicate optimization-based systems in their cognition, at least not universally. Similarly, in competitive environments, it often is desirable for human subjects to exhibit some degree of "irreducible uncertainty" in their behavior in order to evade precise anticipation by their opponents.[79] It is not surprising, therefore, that rational choice theory has proven unable to accommodate a wide range of stable individual behaviors: Such behaviors have evolved in response to decisionmaking environments that often do not themselves conform to the presuppositions of rational choice theory.

[78] For an overview of these findings, see Jon D. Hanson & Douglas A. Kysar, *The Joint Failure of Economic Theory and Legal Regulation*, in SMOKING: RISK, PERCEPTION, AND POLICY (Paul Slovic, ed., 2001).

[79] PAUL W. GLIMCHER, DECISIONS, UNCERTAINTY, AND THE BRAIN: THE SCIENCE OF NEUROECONOMICS (2004).

Prescriptively, the existence of ill-posed and computationally intractable problems also disrupts the claim of optimization-based regimes to comprehensive application. Due to the existence of these types of problems, the limit of the solution frontier for a decisionmaking task in many cases will not be given by rational choice theory or any other available optimization system. Thus, unless one arbitrarily excludes relevant variables or otherwise "edits" the problem in order to yield an optimum solution, some normative benchmark other than conventional rational choice ideals will be necessary in these cases in order to assess the usefulness of decisionmaking techniques. Along these lines, researchers from the heuristics program argue that decisionmaking heuristics generally perform quite well if evaluated according to the criterion of ecological rationality; that is, the fitness of the heuristics for the environment in which they are being deployed, as judged by their relative success at achieving intended aims compared to other realistically possible decisionmaking strategies.[80]

Rationality in Social Choice. The two dominant paradigms for environmental decisionmaking – CBA and the PP – nicely parallel the two conceptions of rational decisionmaking that compete for acceptance within cognitive psychology. In both debates, a sharp contrast has been drawn between decisionmaking techniques that aim, on the one hand, to pursue optimal outcomes through the application of formal analytical systems and, on the other hand, to achieve realistically satisfactory outcomes through less formalized,

[80] Indeed, heuristics researchers argue that a variety of cognitive processes identified in the literature as biases or illusions appear well-adapted when viewed within the richer ecological context that shaped their development, rather than against a rational choice benchmark that is artificially divorced from many of the constraints that characterize real world decisionmaking. *See* Gerd, Gigerenzer, *Fast and Frugal Heuristics: The Tools of Bounded Rationality*, in HANDBOOK OF JUDGMENT AND DECISIONMAKING tbl. 4.1 (D. Koehler & N. Harvey, eds., 2004).

more incremental decisionmaking processes. The former "synoptic paradigm"[81] is reflected both in the expected utility maximization model of rational choice theory and in the applied welfare economic technique of regulatory CBA. Similarly, the latter paradigm of "muddling through"[82] is reflected both in the "ecological rationality" view of decisionmaking heuristics championed by Gigerenzer and others, and in the centuries-old emphasis on foresight and anticipatory care that grounds the PP.[83]

Legal academic treatment of CBA and the PP has likewise tended to parallel the theoretical debate that has taken place within psychology. A few prominent holdouts aside, most scholars writing in the areas of environmental, health, and safety regulation today support the view that CBA is a desirable societal decisionmaking tool that outperforms any other available framework. Moreover, these thinkers often cite evidence from the heuristics and biases literature in support of their claim that CBA serves to discipline and improve collective judgment. Accepting the common interpretation of the heuristics and biases literature that human cognition is prone to systematic error, they argue that CBA helps to overcome such errors by forcing comprehensive, empirical evaluation of policy proposals, including the hazards that a proposal is designed to address, the proposal's expected behavioural and environmental consequences, and the financial expenditures and foregone opportunities that the proposal's enactment will entail.[84]

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[81] Diver, *supra* note __, at __.

[82] Lindblom, *supra* note __, at

[83] *See Introduction: To Foresee and To Forestall*, *in* PROTECTING PUBLIC HEALTH AND THE ENVIRONMENT: IMPLEMENTING THE PRECAUTIONARY PRINCIPLE 1, 4 (1999) (noting that the PP "has its roots in hundreds of years of public health practice"); Sonja Boehmer-Christiansen, *The Precautionary Principle in Germany—Enabling Government*, *in* INTERPRETING THE PRECAUTIONARY PRINCIPLE 31, 38 (Timothy O'Riordan & James Cameron eds., 1994) (tracing the PP to the German principle of *Vorsoge* which means "beforehand or prior care and worry").

[84] *See, e.g.,* Sunstein, *Cognition and CBA*, *supra* note __, at __ (describing "[t]he cognitive argument for cost-benefit analysis" as premised on the likelihood that "predictable features of cognition will lead to a demand for regulation that is unlikely to be based on the facts").

The debate over CBA and the PP can benefit greatly from a broader reading of the psychological literature. Just as supporters of the PP seem to give insufficient regard to the possibility that public demand for regulation may be ill-informed or irrational,[85] proponents of CBA fail to confront the possibility that their maximizing exercise may in some instances fail the test of ecological rationality. As the lessons of the heuristics research program suggest, the aspiration to optimize that lies at the heart of CBA may make little practical sense when applied to a world of complexity. To be sure, an important component of the argument in favor of CBA is that, without disciplined quantification, ordinary individuals are prone to ignore the costs and benefits of decisions that appear "off-screen."[86] The threat of genetically modified "super weeds"[87] looms large, as do the dangers of catastrophic climate change[88] or runaway nanodevices that transform the planet into "gray goo."[89] Less visible, and therefore less attended to according to proponents of the synoptic paradigm, are the vitamin enriched rice strains,[90] the carbon fueled economic gains,[91] and the nanoscale cancer cures[92] that might be foregone if society were to abstain from pursuing novel technologies

[85] Kuran & Sunstein.

[86] HOWARD MARGOLIS, DEALING WITH RISK: WHY THE PUBLIC AND THE EXPERTS DISAGREE ON ENVIRONMENTAL ISSUES 76 (1996). *See also* Howard Margolis, *A New Account of Expert/Lay Conflicts of Risk Intuition*, 8 DUKE ENVTL. L. & POL'Y F. 115 (1997).

[87] *See* Kysar, *Preferences for Processes*, *supra* note __, at __ (describing biological evidence of genetic trait dispersion among neighboring plants from genetically modified crops).

[88] *See* Kysar, *Climate Change*, supra note __, at __ (describing "abrupt climate change scenarios").

[89] *See* Joy, *supra* note __, at __ ("Among the cognoscenti of nanotechnology, this threat has become known as the 'gray goo problem.' Though masses of uncontrolled replicators need not be gray or gooey, the term 'gray goo' emphasizes that replicators able to obliterate life might be less inspiring than a single species of crabgrass. They might be superior in an evolutionary sense, but this need not make them valuable.").

[90] *See* Adler, *supra* note __, at 200 (describing "the creation of a new strain of rice fortified with additional Vitamin A" that may combat "vitamin A deficiency, which can cause blindness and other ills, [and which] affects up to 250 million children worldwide").

[91] *See* LOMBORG, *supra* note __, at 318 ("Despite our intuition that we naturally need to do something drastic . . . about global warming, economic analyses clearly show that it would be far more expensive to cut CO2 emission radically than to pay the costs of adaptation to the increased temperatures.").

[92] *See* Glenn Harlan Reynolds, *Nanotechnology and Regulatory Policy: Three Futures*, 17 HARV. J. L. & TECH. 179, 186 (2003) (speculating that "specially designed nanodevices, the size of bacteria, might be programmed to destroy arterial plaque, or fight cancer cells, or repair cellular damage caused by aging").

and other risky endeavors. CBA forces such "opportunity benefits"[93] on-screen by requiring the regulator to analyze all identifiable effects of a proposed course of action, including the various positive courses of action that might be foreclosed by government regulation. As such, CBA promises to systematize decisionmaking in the administrative state, reducing the chance that officials will overlook *any* potential consequence of government action, whether beneficial or harmful.[94]

Even assuming that the proper goal of risk regulation is social welfare maximization and that existing techniques for valuing costs and benefits do provide "a workable proxy for the criterion of overall well-being,"[95] the CBA practitioner still must be confident that her tools of risk assessment generate reliable data regarding the human and ecological toll threatened by a proposed activity or substance. In this respect, it is a common criticism of CBA that the methodology presumes, by its very nature, a level of data and understanding regarding the consequences of risk-generating activities that generally is non-existent. Moreover, by providing a semblance of order and exactitude where none exists, the results of CBA threaten to obscure the actual severity of uncertainties regarding many environmental, health, and safety risks. In light of such concerns, even proponents of the methodology counsel against "the thought that science and economics, taken together, can produce bottom lines to be mechanically applied by regulatory agencies."[96] The teachings of complexity theory, however, suggest that the uncertainty critique strikes more deeply than

[93] Sunstein, *Precautions Against What?*, *supra* note __, at 9.

[94] SUNSTEIN, RISK AND REASON, *supra* note __, at ix (arguing that, rather than an attempt to maximize overall well-being, "cost-benefit analysis should be seen as a simple pragmatic tool, designed to promote better appreciation of the consequences of regulation").

[95] Matthew D. Adler, *Risk, Death and Harm: The Normative Foundations of Risk Regulation*, 87 MINN. L. REV. 1293, 1393 (2003).

[96] SUNSTEIN, RISK AND REASON, *supra* note __, at 154.

this: It is not merely that CBA may lead to erroneous results, but that it may lead to spectacularly erroneous results.

Unlike many longstanding criticisms of the CBA methodology, this critique cannot be dismissed as striking from outside of the welfarist framework that is presupposed by the economic reform movement. Instead, if the teachings of complexity theory are sound, then environmental, health, and safety dilemmas will, almost by definition, present ill-posed problems that contain "nasty surprises"[97] and other intractable features. In such contexts, the deliberate attempt to optimize may not represent simply an imperfect but useful aid to decisionmaking, as CBA defenders often assert.[98] Rather, it may represent a solution concept that is fundamentally ill-suited to the problem tasks at hand. Because of this misfit, we cannot confidently expect that the errors of CBA will cluster around an "optimal" result – indeed, for ill-posed problems the very notion of an optimum eludes meaningful description. Instead, we must anticipate that the errors of CBA are capable of deviating substantially and unpredictably from decision paths that are easily recognized as desirable, if not necessarily optimal, through less formalistic decision procedures. To give one pressing example, future generations may regard with marvel our present day attempts to meticulously calculate the costs and benefits of anthropogenic climate change. Such studies often lead to a conclusion that the economic benefits of continued fossil fuel consumption more than outweigh the physical, agricultural, and ecological costs that would be averted by restricting emissions, at least in the near term. Accordingly, the optimal greenhouse gas reduction policy under CBA is typically a rather limited one that should not commence for

[97] Farber, *supra* note __, at __.

[98] *See, e.g.,* Richard S. Markovits, *Duncan's Do Nots: Cost-Benefit Analysis and the Determination of Legal Entitlements*, 36 STAN. L. REV. 1169, 1171 (1984) (calling it a "fundamental error" to assume "that proponents of cost-benefit analysis are committed to arguing that the outcome of a cost-benefit analysis ought to be the sole criterion used to determine who should be given the relevant legal entitlement").

several decades.[99] The important lesson from complexity theory, again, is that the CBA consensus on climate change may not merely be wrong; it may be wildly wrong. Moreover, it may be wrong as a matter of *consequentialist evaluation*, the very domain in which CBA proponents proclaim their decisionmaking framework to be most adept. Truly rational regulatory decisionmaking requires some understanding of when it is not optimal to optimize. CBA itself cannot generate such wisdom, for no well-formulated analytical system can be expected to derive its own demise. Instead, what is required in every case is an independent judgment – one that is crafted in light of evolving but always incomplete knowledge, and that is offered in service of reasoned but always reappraisable moral and political commitments.

The argument from complexity should be distinguished from long-standing complaints of scholars that CBA and other formalistic aspects of the regulatory rulemaking process can lead to a situation of "paralysis by analysis."[100] This traditional objection to CBA – that its enormous informational demands bog down the policymaking process to such a degree that, when viewed in light of administrative time and resource constraints, CBA becomes pragmatically irrational – might be thought of as mirroring the category of informationally and computationally daunting problems that the heuristics research paradigm has identified as inappropriate for resolution through optimization procedures. A second, more fundamental objection to CBA, however, is that its subject matter often takes the form of ill-posed problems – that is, problems whose imperviousness to resolution is not driven by a lack of information or computational capacity, but by features inherent to the problems themselves. Because complex adaptive systems contain irreducible levels of uncertainty that

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[99] *But see* Stern; Cline; Weitzman.

[100] Thomas O. McGarity, *A Cost-Benefit State*, 50 ADMIN. L. REV. 7 (1998).

cannot be assumed to be of minor significance, such systems by their nature are likely to present ill-posed problems. In such cases, the heuristics research program of Gigerenzer and others advises the adoption of decisionmaking principles far more pragmatic – and more overtly normative – than the optimization standard of CBA.

As proponents of CBA would be quick to point out, however, the non-optimizing approach of the PP (and related policy approaches such as best availability technology requirements or safe minimum environmental standards) does not come without cost. Most notably, the PP is ill-designed to consider and manage the risks of regulation itself, including the risk that cautious regulation may entail significant opportunity costs. Although one can mount a variety of defenses for this apparent asymmetry,[101] they are fragile defenses that depend at bottom on a wider degree of agreement regarding the need for a fundamental value shift from away economic growth and allocative efficiency toward human flourishing and environmental sustainability as the basic desiderata of social choice. Moreover, even if one accepts the contention of PP proponents that environmental, health, and safety decisionmaking is characterized by deep and abiding uncertainty, it is still far from clear that extreme conservatism is appropriate as a general response to uncertainty. After all, John Rawls – whose difference principle fro distributive equity focused attention on the least well-

[101] In my forthcoming book, *see supra* note __, I argue that the intended domain of the PP has been mischaracterized by its opponents. Rather than an analytical device that aims to provide specific guidance on how to choose and behave in specific policy contexts, the PP is better understood as a moral maxim operating at the level of collective agency, akin to the Hippocratic adage – "first, do no harm" – which applies to physicians at the individual level. Like the PP, the Hippocratic adage also appears to be insensitive to the opportunity costs of behaving with precaution; for that reason, no physician would unthinkingly follow its literal restriction, e.g., by refusing to reset broken bones, inject medicines with painful needles, or undertake other harmful treatments in service of a greater therapeutic benefit. Properly understood, "first, do no harm" is not only, or even primarily a behavioral prescription. It is instead a subtle, but steadfast reminder to the professional so cautioned that her actions carry *distinctive* moral weight and that her patients stand in a position of vulnerability and dependency on the careful exercise of *her* judgment. It is a reminder most basically to *be moral*. Similarly, the PP's requirement that we pause to consider the potentially catastrophic or irreversible consequences of our actions is at bottom a reminder that social choices express a collective moral identity. *Our* identity. An identity that cannot be located within the freestanding optimization logic of CBA, although we need to consider its content more now than perhaps ever before.

off member of society, much as the PP and related policy heuristics aim to focus attention on the worst-case outcome threatened by environmentally uncertain activities – argued that exclusive focus on the worst-case would not be appropriate for determining "how a doctor should treat his patients."[102] Proponents of the safe minimum standards approach within environmental economics also tend to hedge their positions, arguing that fidelity to safe minimum standards should yield when the costs of precaution become "immoderate"[103] or "unacceptably large."[104] Within the legal literature, Farber similarly allows for departure from his strong "environmental baseline" approach to policymaking "when costs would clearly overwhelm any potential benefits" from precautionary regulation.[105]

Although critics sometimes argue that these various safety valves suggest a latent efficiency criterion within the precautionary approach,[106] there is an important distinction that prevents the PP from collapsing entirely into CBA, even granting the addition of some form of cost sensitivity: The PP's understanding of cost is much broader than the notion presupposed by CBA. As Richard Bishop wrote in a seminal article on the safe minimum standards approach, the determination of "[h]ow much [cost] is 'unacceptably large' must necessarily involve more than economic analysis, because endangered species involve issues of intergenerational equity."[107] Similarly, advocates of the PP typically contemplate an open,

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[102] John Rawls, *Some Reasons for the Maximin Criterion*, 64 AM. ECON. REV. 141, 142 (1974).

[103] Ciriacy-Wantrup, *supra* note __, at 252.

[104] R.C. Bishop, *Endangered Species and Uncertainty: The Economics of a Safe Minimum Standard*, 60 J. AM. AG. ECON. 10, 13 (1978). Bishop clearly incorporates sensitivity to opportunity costs in his temperance of the safe minimum standards approach: "To get at total social costs [of implementing the safe minimum standard], any measurable benefits of conservation efforts must be subtracted from out-of-pocket and opportunity costs." R.C. Bishop, *Endangered Species: An Economic Perspective*, cited in Tom W. Crowards, *Safe Minimum Standards: Costs and Opportunities*, 25 ECOL. ECON. 303, 304 (1998).

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[106] *See, e.g.,* Stephen F. Williams, *Squaring the Vicious Circle*, 53 ADMIN. L. REV. 257, 269 (2001) ("[T]he strongest argument for the precautionary principle--that some risks are so huge that they absolutely must not be run--becomes meaningless unless we are ready to consider probabilities."); J. Rolfe, *Ulysses Revisited – A Closer Look at the Safe Minimum Standard*, 39 AUSTRALIAN J. AG. ECON. 55 (1995).

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pluralistic process for making determinations about when and how to apply the principle, suggesting that the decision to relax its dictates might be premised on a wide range of appropriate reasons.[108] Given the momentous and context-specific ethical implications of such determinations, PP proponents are simply unwilling to allow mechanical devices such as risk aversion or option value premiums to substitute for considered, democratic judgment. The problem, though, is that PP proponents fail to provide adequate substantive guidance as to how these various safety valves should be implemented. Given that society is to avoid serious or irreversible harm unless the costs of doing so become "intolerable," how is the notion of intolerability to be understood and operationalized? The PP raises this question and rightly emphasizes that its resolution is far more complicated and value-laden than the CBA procedure would indicate. To date, however, the PP has failed to provide a compelling resolution of its own and has instead tended to turn to a richer substantive framework such as the sustainability paradigm,[109] or simply to equate the results of an idealized democratic decisionmaking process with sound policymaking. In either case, as even its proponents acknowledge, "implementation of the [PP] in a consistent and broadly acceptable manner has been fraught with philosophical, legal, political, and scientific problems."[110]

III. THE PROMISE OF ENVIRONMENTAL ASSURANCE BONDING

An agreeable compromise between the extremes of CBA and the PP may be found in the form of environmental assurance bonding, a policy tool that has been remarkably

[108] *See* The Wingspread Declaration ("The process of applying the Precautionary Principle must be open, informed and democratic and must include potentially affected parties.").

[109] *See* Michael C. Farmer & Alan Randall, *The Rationality of a Safe Minimum Standard*, 74 LAND ECON. 287, 287 (1998) (noting that some "advocates of the precautionary principle expand [safe minimum standard] protections into a comprehensive, strong sustainability objective").

[110] Katherine Barrett & Carolyn Raffensperger, *Precautionary Science*, in PROTECTING PUBLIC HEALTH AND THE ENVIRONMENT, *supra* note __, at 106, 106. *See also* Gary E. Marchant, *From General Policy to Legal Rule: The Aspirations and Limitations of the Precautionary Principle*, 111 ENVTL. HEALTH PERSP. 1799 (2003).

understudied in the academic and policy literatures, despite the vast increase in attention to market-based regulatory instruments over the past three decades. As this Part explains, the environmental assurance bonding approach acknowledges the uncertainty and complexity of biophysical systems by attaching serious financial consequence to the causation of environmental harm, including even those worst-case harms that can be conceived of as theoretically plausible, even though not presently estimable. The approach also, however, acknowledges the strength and dynamism of sociolegal systems by allowing market actors to proceed with potentially beneficial activities despite the existence of a credible risk of harm. Indeed, the assurance bonding device actively marshals the decentralized decisionmaking power of markets as a force for the development of knowledge regarding uncertain substances and activities. As such, the policy tool reflects a high degree of ecological rationality, approaching ill-posed regulatory problems with an aggressive combination of respect for the power of markets, incentives, and technology, and caution before the complexities of nature.

Symmetric Humility. Before addressing more concrete aspects of the environmental assurance bonding device, it is helpful to observe at the theoretical level that CBA and the PP suffer from complementary blind spots – blind spots that should be recognized as such by partisans in the debate even from within their respective theoretical frameworks. For instance, CBA begins with an assumption that government regulatory efforts are especially likely to lead to unintended consequences, lost opportunities, interest group distortions, and a variety of other harmful perturbations of the various complex systems that comprise the regulated market. In order to guard against such harms, proponents of CBA urge a decisionmaking framework that aspires to comprehensive rationality. They believe that requiring regulatory choices to be premised on an explicit and exhaustive accounting of the choices' costs and benefits will force government officials to more reliably promote the public interest than under less formalized decisionmaking procedures.

The limitation of CBA, however, is that it fails to appreciate the parallel manner in which human perturbations of the environment are likely to lead to unintended, unpredictable, and potentially harmful outcomes. Decisionmakers faced with such complex and uncertain problems must resort to a more pragmatic and incremental approach to policymaking, one that includes criteria for guiding action in the absence of a demonstrable optima and that affords flexibility in the face of constantly evolving information regarding the need for and the consequences of regulatory action. CBA instead tends to presume static, linear, well-behaved biophysical systems that regulators can model and manage with precision. In essence, proponents of CBA accept the teachings of complexity theory with respect to sociolegal systems, but not biophysical systems, a critical shortcoming that casts doubt on the belief that CBA is the most ecologically rational approach to environmental, health, and safety decisionmaking.[111] Importantly, one need not suspend the strictly consequentialist-utilitarian philosophical premises of CBA in order to reach this conclusion. Rather, the ecological irrationality critique strikes against CBA on the methodology's own terms. It accuses CBA, in essence, of being insufficiently empirical.

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111 Such asymmetry is well-demonstrated by the frequent conclusion of CBA and risk-risk analysis proponents that technological interventions provide the most cost-effective manner in which to respond to the climate change problem. *See* Wiener, Schelling. Such "geoengineering" interventions – which include cloud-seeding, ocean carbon sequestration, atmospheric dust dispersion, and a host of other ambitious scenarios – reflect an assumption of simplicity and controllability within biophysical systems that proponents of the synoptic paradigm would never accept with respect to sociolegal systems. This asymmetry is especially curious given the historical derivation of market metaphors from evolutionary biology. *See supra* text accompanying note __.

The PP, on the other hand, is premised on the bedrock assumption that biophysical systems are complex, uncertain, and easily perturbed. Indeed, much of the confusion in the literature regarding the merits of the PP stems from a failure to acknowledge that environmental decisionmaking often must precede on the basis of a dauntingly little understanding regarding the objects of regulation. When critics of the PP purport to identify harmful consequences of behaving according to the principle's dictates, they generally assume a stable and relatively complete state of knowledge. Proponents of the PP, on the other hand, regard environmental decisionmaking as an inherently uncertain, evolving, and dynamic process, and they therefore seek to offer a decisionmaking principle that is *procedurally* rational. By providing that "[p]reventive action should be taken in advance of scientific proof of causality," and that "the proponent of an activity, rather than the public, should bear the burden of proof of safety,"[112] the PP incorporates a default assumption of harm and surprise from human alteration of biophysical systems, and promotes a structure for revising the assumption in light of improved knowledge and changed circumstances.

The teachings of decision theory and complexity theory suggest that there may be much merit to such an approach, even if one's goal is simply to promote overall utility. The nature of complex adaptive systems counsels an incremental approach to policymaking – one that specifically contemplates a state of evolving, yet perpetually incomplete information, and that asks its decisionmakers to constantly monitor and adjust policies in light of changed circumstances toward identified goals that are themselves subject to monitoring and adjustment. Decisionmakers, in other words, should engage not in optimization, but in something closer to the approach that Charles Lindblom famously

[112] *Introduction: To Foresee and To Forestall*, *supra* note __, at 8-9.

termed "muddling through,"[113] and that now forms the basis of a significant and well-developed literature on adaptive ecosystem management. Thus, even within the comparatively narrow philosophical framework of CBA, the PP can be seen as an intelligently designed heuristic device that may be more ecologically rational than deliberate optimization techniques, at least when one considers the administrative toll of cost-benefit calculation and the fact that much of environmental decisionmaking concerns ill-posed problems that do not admit of optimal solutions.

The PP, however, also has a blind spot. When read to require affirmative action to guard against all environmental, health, and safety risks that meet some threshold of significance and scientific credibility, the PP quickly threatens to become an unrealistic and unworkable device. As proponents of CBA have taught us, any attempt to guard against environmental, health, and safety risks – including risks that pose catastrophic or irreversible consequences – inevitably will entail a series of ripple effects in the market that may themselves cause harm. The fact that the empirical literature documenting such ripple effects is fairly weak to date does not mean that the effects should be excluded wholesale from consideration. Such an exclusion would represent the very kind of reaction to uncertainty that the PP generally aims to avoid. Properly understood, therefore, the PP can only offer a starting point for societal discussion, a default assumption of extreme conservatism that is to be pondered, contested, and overcome through rules of procedure and substance about which the PP has little to say.

Table 1 reflects these complementary blind spots of CBA and the PP, showing that each methodology exhibits a measure of respect for complexity in only one domain as between biophysical and sociolegal systems. Table 2 then suggests that the complementary

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blind spots of CBA and the PP can be expected to cause the respective methodologies to err in predictable directions in the face of uncertainty. For instance, given the dearth of information regarding the environmental, health, and safety risks of many applications of nanotechnology, such as the free release of nanoparticles into ecosystems, regulators following either decisionmaking paradigm will tend to display bias with respect to the type of error that they incur. By generally presuming that biophysical systems are well understood, resilient, and replaceable, CBA will tend to favour Type I errors, in which regulators permit the release of nanoparticles that turn out to be harmful, rather than entertain the opportunity cost of prohibiting an activity that might be beneficial. In contrast, the PP through its asymmetric precautionary trigger tends to favour Type II errors, apparently content to lament "what might have been" rather than actively permit ecological harm from potentially risky substances or activities.

Table 1		
	Respect for Biophysical Complexity	**Respect for Sociolegal Complexity**
CBA	**No**	**Yes**
PP	**Yes**	**No**

Table 2		
	Substance or Activity Harmful	**Substance or Activity Harmless**
CBA	**Type I Error**	**Benefit Allowed**
PP	**Cost Avoided**	**Type II Error**

Assuming that deep scientific uncertainty will continue to attend much of environmental, health, and safety policymaking, the question then becomes how to accommodate such uncertainty within the regulatory framework. The CBA approach seems to assume that uncertainty is simply addressed *out there*, through institutions and procedures that lie beyond the reach of the policy decision under inspection. This approach comports with the general permissiveness adopted in market liberal societies toward private action. Following the harm principle articulated by John Stuart Mill, such societies tend to place the burden on government regulators to persuasively demonstrate the reality and severity of an action's harmful effects before it may be curtailed. A basic thrust of the PP approach to environmental law and policy is precisely to upset this longstanding allocation of the burden of proof, particularly in areas that are thought to be characterized both by scientific uncertainty and by the potential for serious or irreversible harmful effects. At present, nanoscale science and engineering appears to be just such an area. Thus, a literalist interpretation of the PP would counsel blocking wide deployment of nanoparticles and other fruits of nanoscale science and engineering, at least until their safety and efficacy had been demonstrated to the satisfaction of regulators. Such a strict stance may be undesirable for the reasons described above: Nanoscale science and engineering research promises potentially dramatic benefits, in addition to risks, including benefits which themselves take the form of improvements to environmental sustainability and human health.

What is needed, then, is some mechanism for exhibiting symmetric humility – that is, awareness of and respect for the problems of uncertainty and complexity as they characterize *both* biophysical and sociolegal systems. Environmental assurance bonding offers promise in this respect.

Environmental Assurance Bonding. Under an environmental assurance bonding scheme, before commencing an activity with uncertain but potentially serious adverse effects, regulated firms would be required to post a bond "equal to the current best estimate of the largest potential future environmental damages."[114] The bond would be returned to the firm "if and when the agent could demonstrate that the suspected worst-case damages had not occurred or would be less than was originally assessed."[115] If damage did occur, the bond funds would be available to rehabilitate the affected environment or to compensate injured parties. As one can see, such an approach "combines the 'polluter pays' principle with the 'precautionary' principle, providing for internalization of costs where harm is possible but damages are uncertain."[116] In essence, the bonds work to shift the burden of proof off of regulators and onto the promoters of potentially harmful actions, just as supporters of the PP have long advocated.[117] However, unlike a strict interpretation of the PP – which would essentially ban a proposed activity, substance, or technology until its promoters had successfully demonstrated the absence of risk – the environmental assurance bonding approach allows private action to proceed, albeit under the revised incentive structure created by the bond posting requirement.

A variety of policy design considerations would need to be addressed. For instance, environmental assurance bonds might be used either to guarantee performance of an environmental standard, such as reclamation of a former mining or logging site to a specified set of conditions, or to guarantee payment of a predetermined amount of money, such as a level of damages estimated to be necessary to compensate third parties for harm that might be imposed by an uncertain activity. In addition, the financial instrument actually used to

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[114] Costanza & Cornwell, *supra* note __, at __.

[115] *Id.* at __.

[116] Dana Clark & David Downes, What Price Biodiversity?: Economic Incentive and Biodiversity Conservation in the United States (1995) (citing Costanza & Cornwell, *supra* note __, at 12).

[117] *See* COMMON, *supra* note __, at 215-16; Blomquist, *supra* note __, at 553-54 (stating that environmental assurance bond "systems can shift much of the burden of proof from the public to the producer in resolving uncertainty as to damages associated with new products"); Gerard, *supra* note __, at 189 (noting that "the bond shifts the burden of proof of a legal dispute from the damages party to the polluter"); Ian Bowles, David Downes, Dana Clark, & Marianne Guérin-McManus, *Economic Incentives And Legal Tools For Private Sector Conservation*, 8 DUKE ENVTL. L. & POL'Y F. 209, 234 (1998).

satisfy a bonding requirement could take one of several forms: (1) collateral bonds such as cash deposits, certificates of deposit, letters of credit, or security pledges, (2) so-called "self bonds," which consist of legally binding promissory obligations from regulated entities that pass certain tests of financial soundness, or (3) surety bonds which constitute a guarantee from a third party to either perform the defaulted obligation or pay funds to the regulating agency. The surety bond approach is likely to be the most attractive, both because it tends to be associated with lower costs for regulated firms,[118] and because it offers the prospect of marshalling the information-generating and risk-evaluating capacities of surety companies in service of environmental policy goals. Surety companies would price bonding services based not only on the creditworthiness and compliance history of the regulated firm, but also on the estimated likelihood and severity of harm occurring. This would create a strong incentive for firms to reduce the uncertainty surrounding their proposed activities, either by investing in the advancement of scientific knowledge or by switching to less dangerous alternative activities. Thus, in the competition for capital, those projects, products, or technologies posing less severe potential environmental impacts would obtain a cost advantage over alternatives.

From the perspective of regulated firms, environmental assurance bonds may provide a more equitable policy tool than alternatives such as environmental taxes or auctioned pollution permits. Because taxes and auctioned permits impose a nonrefundable fee applied at the time of use, they presuppose an accurate prediction of the long-term costs of the regulated activity. When regulators lack such an accurate prediction, currently imposed environmental fees run the risk of overdeterring private activity. The environmental assurance bond, on the other hand, explicitly allows for uncertainty by

[118] *See* Ferreira & Suslick, *supra* note __, at 43.

requiring a pledge of funds to cover the worst-case scenario, but allowing periodic refund of such funds as uncertainty dissipates. Assuming that accounting and tax treatment of pledged amounts are properly aligned,[119] under the environmental assurance bonding approach "the efficiency advantages of economic incentives can be reaped without unduly penalizing current economic agents for the cost of unknown future damages."[120]

The most difficult analytical and practical aspect of environmental assurance bonding is determining what amount of financial assurance must be pledged.[121] The existing economic literature tends to assume that the role of environmental assurance bonding is simply to guarantee performance according to some prescribed environmental, health, or safety standard.[122] Moreover, as David Gerard has stressed, "bonding promotes regulatory compliance, but it in no way suggests that the standard promulgated by the regulations is necessarily efficient."[123] Thus, commentators see the chief benefit of bonding requirements to be one of mitigating the risk of default, rather than serving more general environmental policy goals.[124] Likewise, commentators tend to believe that well-known damage valuations are a necessary for environmental assurance bonding schemes to be effective.[125] Such discussions implicitly assume that regulators operate in a well-characterized policy space, wherein thorough empirical understanding of hazards can enable regulators to determine the

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119 *Id.* at __.

120 *See* Intarapravich & Clark, *supra* note __, at 66, and Ferreira & Suslick, *supra* note __, at 51, for discussions of this issue.

121 *See* Doneivan F. Ferreira & Saul B. Suslick, *Financial Assurance Bonds: An Incentive Mechanism for Environmental Compliance in the Oil Sector*, Brazilian Petroleum and Gas Institute – IBP31800 (2001);

122 *See* Ferreira & Suslick, *supra* note __, at 50 ("Setting the appropriate bond requirement (amount) may be one of the greatest predicaments within the bonding system. If bonds are set too low, the system may not provide the desired incentive effect. On the other hand, setting bonds too high may discourage investment in the sector.").

123 Gerard, *supra* note __, at 190.

124 Gerard, *supra* note __, at 195 ("The underlying motivation [for bonding systems] is the high default risk on the side of the agent.").

125 *See* J.F. Hegren, J.A. Herriges, & R. Govindasamy, *Limits to Environmental Bonds*, 8 ECOL. ECON. 109 (1993).

"optimal" level of precaution. An alternative viewpoint would regard the generation of empirical understanding as part and parcel of the policymaking process itself, such that a partial aim of the bonding requirement would be to shift society closer to an epistemic position in which it even makes sense to talk about "optimal" levels of precaution. From this perspective, bond posting requirements would not be set at an "optimal" level, but at a level commensurate with the worst-case harm scenario that is threatened by a proposed activity and that meets some threshold standard of plausibility. This approach would require the development of new analytical tools for imagining and characterizing uncertain threats. Proponents of precautionary environmentalism would regard such tools as long overdue.[126] Nevertheless, some commentators argue against setting bond requirements according to worst-case scenarios on the ground that reputational costs and ex-post tort liability threats provide additional compliance incentives to firms, making the "optimal" bond requirement less than the worst-case extreme.[127] Again, this argument emerges from a policy framework in which scientific understanding and empirical information are treated as exogenous inputs to the policymaking process, rather than features of policy spaces that environmental assurance bonds themselves might aim to influence.

This discussion should not be read to suggest that the environmental assurance bonding approach is free of limitations. To begin with, actual historical experience with the policy instrument in the context of mining reclamation has generated decidedly mixed

[126] Experience with worst-case scenario analysis could have been better developed had the National Environmental Policy Act been interpreted to require such analysis. *But see* Robertson v. Methow Valley Citizens Council, 490 U.S. 332, 356 (1989). Guidance provided by the Council on Environmental Quality represents one effort to develop a threshold standard of plausibility for worst-case scenario analysis, although observers believe the guidance in practice has deterred agencies form undertaking valuable consideration of extreme possibilities. *See* 40 C.F.R. § 1502.22(b)(4) (requiring agencies to evaluate "reasonably foreseeable . . . impacts which have catastrophic consequences, even in their probability 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"), and Hodas, *supra* note __, at 44 (critically assessing the CEQ regulations).

[127] *See* Gerard & Wilson, *supra* note __, at 1100.

results. In 1977, the United States Congress passed the Surface Coal Mining and Reclamation Act in light of the large number of mining sites that lay abandoned and reclaimed across the country. The Act established performance requirements for the reclamation of completed mining sites and required mining permit holders to either achieve the requirements or pay an amount necessary for public entities to achieve them. In addition, permit holders are required before the commencement of operations to submit a reclamation plan and post a reclamation bond in order to ensure compliance with the reclamation requirements.[128] Despite the apparent theoretical advantages of bonding as an incentive device for environmental compliance, use of the device in the mining sector has repeatedly disappointed, chiefly due to the unwillingness of regulators to demand bond amounts at levels adequate to ensure coverage of actual reclamation costs.[129] Colorado's Summitville Mine, for instance, required over $150 million in reclamation costs due to water contamination from the use of cyanide leaching at the site, yet the financial assurance bond posted for the mine had been only approximately $5 million. The Summitville subsidiary and its parent company filed for bankruptcy, abandoning the site to the state.[130] Experiments with environmental assurance bonding in other regulatory areas confirm that the problem of understated bond amounts is significant. In Indonesia, for instance, the government required the posting of restoration bonds in order to obtain logging concessions, yet the per hectare bond fee was set at only a fraction of actual reforestation

[128] Reclamation bonds also have been required in Canada, Australia, and several nations in Southeast Asia. *See* Intarapravich & Clark, *supra* note __, at 61 tbl. 1.

[129] *See, e.g.,* Craig B. Giffin, *West Virginia's Seemingly Eternal Struggle for a Fiscally and Environmentally Adequate Coal Mining Reclamation Bond Program*, 107 W. VA. L. REV. 105 (2004); Gerard, *supra* note __, at 194 (noting that a General Accounting Office study in 1986 determined that of 556 hardrock mining operations in ten states on Bureau of Land Management lands, only one operator had been required to furnish a bond); Todd S. Hageman, *Comparing the Effectiveness of Oil and Gas with Coal Surface Damage Statutes in Oklahoma: Bonding Producers and Operators to Land Reclamation*, 46 OKLA. L. REV. 291 (1993).

[130] *See* Roger Flynn & Jeffrey C. Parsons, *Ensuring Long-Term Protection of Water Quality at Colorado Mine Sites*, 30-JUNE COLO. LAW. 83 (2001).

costs, thus leading to widespread forfeiture of posted bonds rather than actual environmental performance.[131]

Additionally, the long latency periods likely to be at issue for many environmental, health, and safety risks – including those that might eventually be identified in relation to nanotechnology – creates a practical impediment to the implementation of an environmental assurance bonding system, given that cause-effect relationship are likely to be especially difficult to predict and quantify.[132] As David Gerard notes, "[s]urety providers may respond to [such] uncertainty by requiring a higher percentage of the bond as a premium, requiring substantial collateral, or simply refusing to underwrite the bond."[133] A further option for the surety provider is to require the regulated entity to better develop scientific understanding of the environmental, health, or safety threat at issue. Developing private information regarding the likelihood of the regulator's worst-case scenario thus would become a task with economic benefit to the firm, rather than an exercise that firms arguably have positive incentives *not* to pursue under current law.[134] Proponents of the PP might also argue that, in the event a proposed activity is deemed to be uncoverable by the financial industry, then society should be relieved that the activity will not proceed. After all, the point of the environmental assurance bonding requirement is to incentivize ex ante consideration of potential ex post harms, whenever those harms might possibly occur. Future generations, in that sense, are not exempted from the sphere of regulatory concern. An alternative approach – one more solicitous of private economic activity – would be to apply

[131] *See* David O'Connor, Managing the Environment with Rapid Industrialisation: Lessons from the East Asian Experience 130. *See also* Paul Steel & Ece Ozdemiroglu, *Examples of Existing Market-Based Instruments and the Potential for their Expansion in the Asian and Pacific Region*, in Financing Environmentally Sound Development 169, 177 (documenting a similar problem in the Philippines).

[132] Gerard & Wilson, *supra* note __, at 1100 ("Because of uncertainty as time horizons expand, surety providers are unlikely to underwrite bonds over time horizons where there is considerable uncertainty.").

[133] Gerard, *supra* note __, at 191.

[134] Mary Lyndon, Wendy Wagner.

environmental assurance bonding requirements as part of a phased "stewardship regime," in which initial bonding requirements are replaced over time, first by a publicly-managed but industry-financed pooled fund insurance mechanism and, eventually, by a full public assumption of responsibility and liability for the potentially harmful effects of the regulated substance or activity.[135]

Finally, the bonding requirement is likely to impose liquidity constraints on firms that might, in turn, slow investment and innovation.[136] Liquidity constraint problems are alleviated in part through the use of third-party surety firms.[137] Alternatively, if firms are required to post collateral bonds directly, then posted funds could be made interest-bearing and fully refundable such that, even while in escrow, they might be used to collateralize loans for other investments. Again, this approach would have the advantage of creating incentives for private actors to develop better knowledge regarding the likelihood and severity of worst-case risk scenarios, since that information would be necessary to properly estimate the value of the collateral bond in the secondary market. More generally, however, the threat posed by environmental assurance bonding schemes to capital availability is one that, at least for promoters of the PP, should not necessarily disqualify such schemes from consideration. Markets only work to optimize under a given set of constraints; for too long in the eyes of PP proponents, industrialized nations have failed to fully include environmental externalities within the set of constraints governing private economic behavior. By shifting to a stance of symmetric humility, long-term economic and development equilibriums will be shifted toward a "softer," more environmentally stable path. In that sense, a retraction of capital

[135] *See* Gerard & Wilson, *supra* note __, at 1102.

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[137] *See* Gerard, *supra* note __, at 191.

availability under an environmental assurance bonding regime would simply represent the transformation of a growth economy to a sustainable economy.

CONCLUSION

Physicist Richard Feynman famously presaged the field of nanotechnology by observing that "there's plenty of room at the bottom."[138] The teachings of complexity theory suggest that there also is ample room at the top, where our reductionist habit of subdividing scientific investigation and knowledge into separate, narrowly delineated subject areas has left a gap of awareness and comprehension regarding complex adaptive systems. Moreover, just as scientists expect to achieve interdisciplinary convergence at the nanoscale – fusing biology, physics, chemistry, and information technology into a single atomic science – so too must policy analysts seek convergence at the macroscale, integrating moral philosophy, economics, psychology, and legal knowledge into a unified, pragmatic framework for societal risk decisionmaking. CBA and the PP represent complementary attempts to manage such a convergence, focusing on the threats posed to human well-being when regulators display insufficient respect for the uncertainty and complexity of, respectively, markets and ecosystems. Despite – or perhaps because of – these deliberate focal points, each decisionmaking paradigm is flawed by a failure to recognize the challenges posed by uncertainty and complexity in the alternative sphere of concern. In order to fully address the issues that threaten our environmental future, policymakers must therefore begin to embrace an ethic of symmetric humility. One concrete method for doing so is through greater use of environmental assurance bonding.

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[138] Richard P. Feynman, *There's Plenty of Room at the Bottom*, ENG. & SCI. (1960).