the role of the environment—as another system—is then natural in seeking answers.

I am in good company when accused of the *H*-theorem "mistake." Still, Ludwig Boltzmann dealt with the evolution of a many-body system that is classical and isolated. In that classical setting, probability was a fault of an observer ignorant of the system's precise state. Boltzmann's *Stosszahlansatz* postulates uncorrelated trajectories and is a way of representing that ignorance. Although the Boltzmann equation is useful, calling on *Stosszahlansatz* to prove the *H*-theorem—that is, the second law of thermodynamics—was suspect. Evolution is deterministic and reversible, so while observers' ignorance may increase, microscopic entropy of the closed system cannot change. Moreover, the information and hence ignorance of observers is irrelevant for classical dynamics.

As I show in my article, in our quantum world probabilities arise via entanglement. A single photon that escapes with information about the fate of Schrödinger's cat is enough to decohere the cat's state. An observer can never catch up with the photon, so reversibility of the equations of motion notwithstanding, information loss can be irreversible for prosaic yet compelling reasons. The resulting entropy production can be accounted for by decoherence.[5]

The whole measurement (or Schrödinger's cat) setup starts far from equilibrium. Quantum Darwinism and decoherence show why, in such nonequilibrium multipartite settings, pointer states—and not their superpositions—survive and information about them is amplified and recorded in many copies by the environment. Both the nonequilibrium setting and the division of the universe into systems are needed to state the problem. When certain assumptions are needed to state the problem, surely they can be used to solve it.

References

1. M. Zwolak, W. H. Zurek, *Sci. Rep.* **3**, 1729 (2013); A. Streltsov, W. H. Zurek, *Phys. Rev. Lett.* **111**, 040401 (2013).
2. L. D. Romero, J. P. Paz, *Phys. Rev. A* **55**, 4070 (1997).
3. C. J. Riedel, W. H. Zurek, *Phys. Rev. Lett.* **105**, 020404 (2010); *New J. Phys.* **13**, 073038 (2011); M. Zwolak, C. J. Riedel, W. H. Zurek, *Phys. Rev. Lett.* **112**, 140406 (2014).
4. W. H. Zurek, *Phil. Trans. Roy. Soc. A* **356**, 1793 (1998); *Rev. Mod. Phys.* **75**, 715 (2003).
5. W. H. Zurek, J. P. Paz, *Phys. Rev. Lett.* **72**, 2508 (1994).

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Many approaches to climate change policy

I found Paul Higgins's article, "How to deal with climate change" (PHYSICS TODAY, October 2014, page 32), a useful and balanced summary of the high-level policy options that are available. However, he omits a few points that are often glossed over in discussions of the issue.

First, it is true that we will have to adapt to climate change. Even if carbon dioxide levels were to stabilize today, Earth would continue to warm for decades, sea levels would continue to rise for centuries, and biological systems from fisheries to forests would respond to those changes. But adaptation without mitigation is folly. If CO_2 levels do not stabilize, any attempts to adapt to climate change will eventually be insufficient and will need continual augmentation. In that unstable scenario, the costs of adaptation will eventually exceed those of mitigation.

Second, the biological world generally is much less adaptable than humans. Some biological systems may simply not be able to adapt fast enough and may fail catastrophically. Given our huge reliance on the services provided by biological systems, figuring in the societal loss from those systems' inability to adapt should push the balance even further toward mitigation.

Third, although Higgins mentions the immediate loss to our economy due to the degradation of biological systems, he does not mention the decimation of biological capital that would result from climate change. I argue that the planet's most valuable natural resource is the vast store of information in the DNA of the millions of species that have developed over a billion years of evolution. Humans have barely started exploiting that treasure trove for new medicines, foods, materials, and more. Yet biologists tell us that even without climate change, we are in the midst of the sixth great extinction on this planet. Climate change will only accelerate the loss of species. Shouldn't that particular loss figure into calculations of the costs of climate change and the debate over mitigation versus adaptation?

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■ **Higgins replies:** Brian Cluggish argues for aggressive mitigation based on the potential impacts of climate change on biological resources. That is a perfectly defensible policy preference for anyone concerned about the consequences of disturbing the climate system. However, other readers may be more risk averse to climate policy. Those who own or work in coal-fired power plants, for example, might worry about responding too aggressively. The societal risks of climate change and climate policy are highly asymmetric but a full discussion of response options must account for the full spectrum of views.

At times, Cluggish presents climate policy as zero-sum—more attention to one approach means less attention for others. That is a false choice.

We could simultaneously mitigate, adapt, geoengineer, and build the knowledge base; comprehensive risk management would involve a combination of approaches. Approaches might come at the expense of one another if resources—time, money, human capital, or political will—are limited, but approaches could also encourage and reinforce each other.

Cluggish mistakenly interprets my article as promoting one policy approach at the expense of another. My article, by design, leaves policy preferences to readers because choosing among the options involves personal preferences, interests, and moral or ethical judgments. Science can inform but not determine those. A fair and objective presentation of the options gives readers the best chance to understand the tradeoffs and decide for themselves what combination of approaches would be best.

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