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New Theory for Increasingly Tangled Banks

Theory has fallen out of fashion in the sciences, in favor of data collection and number crunching. But the conceptual frameworks provided by theory are essential for addressing society's most complex and urgent problems.

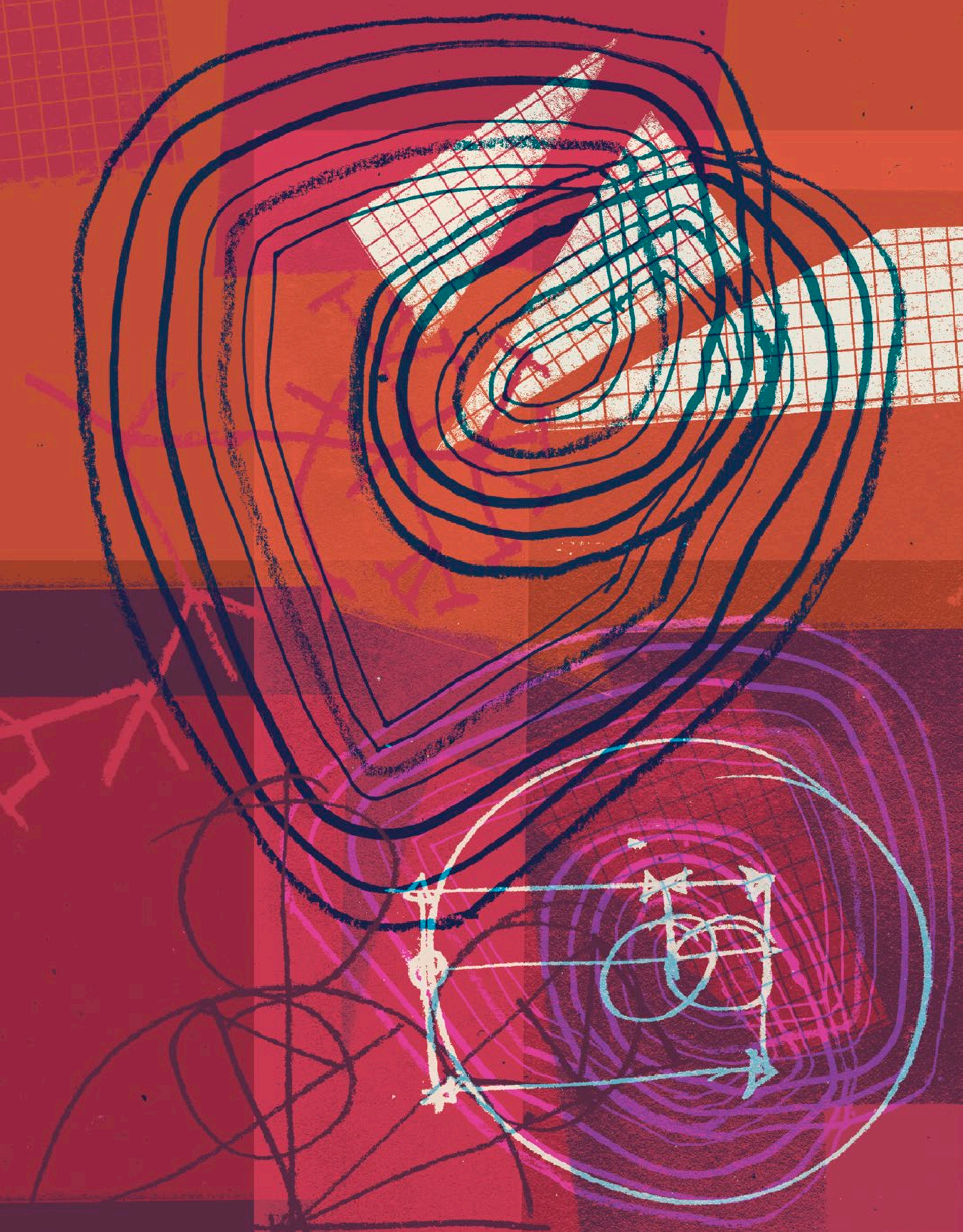
Decades before the COVID-19 pandemic demonstrated how rapidly infectious diseases could emerge and spread, the world faced the AIDS epidemic. Initial efforts to halt the contagion were slow as researchers focused on understanding the epidemiology of the virus. It was only by integrating epidemiological theory with behavioral theory that successful interventions began to control the spread of HIV.

As the current pandemic persists, it is clear that similar applications of interdisciplinary theory are needed to inform decisions, interventions, and policy. Continued infections and the emergence of new variants are the result of complex interactions among evolution, human behavior, and shifting policies across space and over time. Due to this complexity, predictions about the pandemic based on data and statistical models alone—in the absence of any broader conceptual framework—have proven inadequate. Classical epidemiological theory has helped, but alone it has also led to limited success in anticipating surges in COVID-19 infections. Integrating evolutionary theory with data and other theories has revealed more about how and under what conditions new variants arise, improving such predictions.

AIDS and COVID-19 are examples of complex challenges requiring coordination across families of scientific theories and perspectives. They are, in this sense, typical of many issues facing science and society today—climate change, biodiversity decline, and environmental degradation, to name a few. Such problems occupy interdisciplinary space and arise from no-analog conditions (i.e., situations to which there are no current equivalents), as what were previously only local perturbations trigger global instabilities. As with the pandemic crises, they involve interdependencies and new sources of uncertainty, cross levels of governance, span national boundaries, and include interactions at different temporal and spatial scales.

Such problems, while impossible to solve from a single perspective, may be successfully addressed by integrating multiple theories. This approach represents science as seeking integration and robustness rather than pursuing reduction and simplification. However, to do this interdisciplinary work in response to a crisis, it is necessary to have first invested in work on new theory, both within and across fields, well beforehand.

Strengthening theory so that it is available when needed requires changes to the way science is currently funded and conducted. Today, theory has fallen out of fashion, and it



struggles to find financial and intellectual support. To reinvigorate theory, funding agencies must prioritize it, focusing financial resources but also ensuring that theory does not consistently lose out to trendy data-driven approaches. The education system must enhance understanding of how theories connect to models and data and reinforce theory's fundamental usefulness. And it is time to open and strengthen lines of communication between theoreticians and policymakers so that theory can help guide the decisions that need to be made.

The rise and fall of theory

Almost all research on natural phenomena depends on theory. Relativity theory, evolutionary theory, and plate tectonics are examples of theories that have significantly advanced their own fields and brought disparate fields together. Theories catalyze understanding by identifying the key mechanisms underlying patterns and presenting plausible explanations that link possible causes with effects—thereby providing a framework for predicting possible outcomes and unobserved phenomena. By capturing the essential features of a system, scientific theories account for the natural world's complexity.

Theories are essential to scientific progress because they guide what gets observed or measured, what experiments are conducted, and how the resulting data are interpreted. When Copernicus proposed that the Earth circled the Sun, his heliocentric theory replaced the long-held geocentric explanation for planetary motions. Heliocentrism was subsequently supported by empirical evidence, and it formed the basis for the development of formal laws for planetary motion as well as Newton's discovery of gravity.

As in other scientific fields, theory has played an essential role in the development of evolutionary, ecological, and environmental sciences. Perhaps the best-known example is Darwin's theory of evolution by means of natural selection. Darwin derived his key principles from careful observation, geology, fundamental ecological principles, and the widespread use of artificial selection during the 1800s. Despite unleashing heated controversy, the theory of natural selection has withstood decades of scrutiny and helped build the foundations for modern evolutionary, ecological, economics, and behavioral research.

In the field of ecology, both mathematical and conceptual theory complemented real world observation to advance understanding during the early twentieth century, in what has been called the golden age of ecological theory. These include Pearl's law of logistic population growth, core mechanisms underlying disease dynamics, and Lotka's and Volterra's models for interspecific interactions. The field of ecology has advanced through a deep integration of theory and experimentation.

Despite the rich history of theory and its importance to scientific progress, its current status has diminished. The reasons for this decline are many, but at the center is the changing role of data. As data have become ubiquitous, and as new and sophisticated statistical techniques have risen to the fore, researchers and funders have been increasingly incentivized to bypass theory. However, data alone are not enough to guide science, and the data that have most effectively advanced scientific understanding have been grounded in questions that derive from theory.

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As data have become easier to collect and analyze, they have become uncoupled from theoretical constructs. Not all that long ago, what data to collect and how to collect them were decisions based on animating questions, with theory as their foundation. Recent technological advances have automated data collection, and huge amounts of data can now be collected and rapidly analyzed. For example, administrative data are routinely collected for various purposes, but may be used later to inform public policies and procedures. While such data can lead to powerful insights, their collection is not predicated on any theory or associated questions, limiting their utility.

Divorced from guiding questions, efforts to collect and analyze huge data sets have proven primarily exploratory and descriptive. The Human Genome Project, for instance, aimed to catalogue the human "blueprint" using two new technologies: gene mapping and DNA sequencing. Although some of the results have assisted in identifying genes responsible for certain diseases, gene sequences alone reveal little about gene expression and phenotype, and the blueprint metaphor is now recognized as misleading. Similar efforts such as the Barcode of Life as well as the increasing popularity of using large biological datasets (informally known as omics data) and conducting biodiversity surveys are all examples of data

Illustration by Shonagh Rae

that are collected because they can be gathered easily and in huge quantities. Each of these produces catalogs of what exists that are descriptive but not explanatory. And without theory, they do little to advance understanding.

Also contributing to the decline of theory is a growing confusion between theory and models. Theory is often represented by physical, conceptual, or mathematical models. These tools can be integrated with data to incorporate the role of chance, represent uncertainty, and inform the application of theory to particular situations. For example, models of species-area relationships test aspects of the theory of island biogeography in specific locations. Other models can test epidemiological theory under complex disease transmission scenarios. While theory and model are treated as synonyms in many disciplines, they are not: models may be specific representations of theory, but they may also lack a theoretical basis. Prediction and forecasting can be approached from either a theoretical or a nontheoretical (e.g., purely statistical) perspective. Although purely statistical models can be useful in certain applications and in deriving short-term projections, they may not allow the robust understanding and interpretation that is afforded by models based on theory.

Funding agencies have exacerbated the issue by focusing resources on data without attention to developing underlying conceptual frameworks. Many devote significant efforts to requiring data management and sharing plans, open access to data, and the establishment of long-term data repositories. By funding national synthesis centers, the National Science Foundation (NSF) has emphasized synthesis of existing data without explicit expectation of underlying theory. According to our analysis of active awards made by NSF's Biological Sciences Directorate, only about 5% of funded projects propose the development of new theory or mechanistic understanding. The decline in funding for theory is not a recent development, and this percentage has not changed much over the past 20 years. What has changed is a strong recent emphasis on computational modeling, artificial intelligence, and large-scale data modeling to reveal cause-and-effect relationships.

In our experience, peer review of grant proposals can also work against theory-based or theory-building research. Empirical scientists are often uncomfortable reviewing theory, models, and equations. But without knowledgeable peer review, theoretical research suffers in the hierarchy of projects recommended for funding and thus loses prominence among practicing researchers. We have seen evidence that theoretical proposals are sometimes considered underdeveloped because the approaches proposed are often less concrete than those needed to design a survey or an experiment. And many contemporary reviewers of theoretical proposals question the relevance of theory to the real world—particularly its reliance on assumptions to extract fundamental features from complexity. Finally, the perception that only theoreticians can evaluate theoretical proposals is common, promoting the view of theory as an offshoot rather than a core component of mainstream research.

We also wonder whether diminishing appreciation for and understanding of theory is rooted in a decline in teaching abstract thinking. Introductory biology textbooks today are rich in facts, details, and examples but light on theory. One popular biology textbook runs to 1,344 pages; only thirteen of these pages mention theory explicitly. Following a major study about a decade ago, educators have increasingly focused on hands-on exercises in undergraduate curricula. Although these active learning techniques successfully engage diverse groups of students to address specific questions or problems, it can be difficult to incorporate underlying theory into exercises focused on solving a particular problem or question. As a result, the teaching of theory is left to graduate education, and many learners miss training in abstract thinking and its philosophical and quantitative underpinnings. The golden age of theory is over, and this shift has significant implications for the utility of research and its insights for policy.

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Why interdisciplinary theory is needed

The power and utility of theory and mechanistic understanding cannot be replaced by ad hoc analysis of data to find patterns. But even existing field-specific theories may provide incomplete roadmaps for tackling the most complex problems and challenges. Ultimately, when theories are integrated across disciplines, their power is compounded. Working with interdisciplinary theory relies on a quantitative approach that includes mechanistic models as well as honest representations of

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uncertainty, and thus results in more powerful predictions for specific—and often unanticipated or novel—situations. Furthermore, the bridging effect of such theories provides a common conceptual framework, a baseline for communication among communities, and a force to advance understanding between disciplines.

The complex challenge of climate change provides an instructive example. The greenhouse effect and the mechanisms by which radiation from the atmosphere warms the planet's surface have long been understood; the strength of the greenhouse effect depends on the amount of greenhouse gases in the atmosphere. Data chart increases in greenhouse gases, and existing theory outlines clear steps toward halting climate change. However, implementing these steps and halting or reversing global warming has so far failed because the steps are fraught with economic, political, cultural, and behavioral complexities. Thus there is a roadmap to address climate change, but it is incomplete. Climate change cannot be addressed without interdisciplinary theory that brings together understanding of greenhouse gas emissions, atmospheric and oceanic circulation drivers, human behavior, and policy constraints, including both material and ethical interests.

New interdisciplinary theory is especially important for policy because the limitations and challenges facing policymakers stem in part from treating problems as unidimensional or unidisciplinary. Integrated theory brings together observations from disparate fields, which then spurs new research questions and redirects attention in ways that advance knowledge of the whole system. Social-ecological systems theory, for example, provides insights for navigating future challenges, acknowledging that interactions among key mechanisms are far more dynamic, uncertain, and complex in today's hyperconnected world. This interdisciplinary approach is implicit in many of the most influential theories of the past—such as plate tectonics, which notably combines earth science, physical geography, continental drift, and seafloor spreading. Similarly syncretic theories will be necessary to address future problems, but generating these ideas, and nurturing these researchers, requires deliberate actions.

Future steps

A renewed focus on theory—enhancing existing theories, building new integrative interdisciplinary theories, and putting them to use—will require change at multiple levels. We focus on three areas. First, researchers and funders must prioritize theory as they allocate their attention, effort, and financial resources. Second, theory must be reinserted into curricula at all educational levels, with a concerted effort to engage a wide swath of the public to understand how theories work and why they are so useful. Finally, theory must be put to use by policymakers, which will require new lines of communication and cooperation among researchers, educators, funders, scientific societies, and policymakers.

Funding agencies must shift more funding and overall effort toward supporting theoretical research. Our call for this echoes one from 15 years ago, when a National Academies panel called for increased funding for theory in biology—an increase that has yet to be realized. There have been initiatives to encourage theoretical research, but none succeeded in creating lasting change. From 2007 to 2012, for example, NSF's Advancing Theory in Biology program supported 42 awards specifically aimed at developing new theories that crossed levels of biological organization and engaged all programs in biological sciences as well as others across the foundation. At the time, this program stimulated tremendous excitement about theory, attracted theoreticians across a broad spectrum of disciplines, and supported innovative theoretical approaches. It boosted theoretical research, but only over the short term. Such programs are more effective when, as with NSF's existing Dynamics of Integrated Socio-Environmental Systems program, they persist and are well-funded. Moreover, the focus should be on targeted programs that explicitly support integrated theory across the sciences.

NSF and other agencies should also develop ways to ensure that funding decisions more broadly incorporate consideration of the role of theory in proposed work. Interestingly, funding priorities for divisions and programs in the Biological Sciences Directorate at NSF include attention to theory at every level (molecular, organismal, ecological, evolutionary), yet this is not reflected in current awards. Reviewers, review panels, and program directors should be charged by leadership to consider theory as an important basis for funding. Increased representation of theoreticians throughout the agency would prompt agency officials and peer reviewers to understand and support the importance of theory and its development. Finally, beyond NSF, a cross-agency assessment of the status of theory in the sciences would complement the previous National Academies report and lead to interagency initiatives to advance theory as integral to their missions.

Making full use of theory in decisionmaking requires that education incorporate theory and abstract thinking skills into the teaching of science. Moving primary science education away from facts that must be memorized and toward approaches that stimulate children's curiosity and their natural ability to think abstractly can introduce them to the practice of using theory to understand the world around them.

In addition, undergraduate and graduate education needs more focus on theory. In light of new abilities to harvest data and use computation, this approach should explore how to pose questions based on theory, how to collect the appropriate data, how to represent theory quantitatively in mechanistic models, and how to interpret the data collected. Future scientists must understand how to construct analytical frameworks to interpret data as well as how to extract general insights from specific studies.

In policy, theory's great strength is its ability to bridge disparate worlds and communities, serving as a unifying conceptual framework for problem-solving. It holds promise for providing a common language that surpasses disciplinary-specific mechanisms or constraints by forcing participants to articulate shared goals and find ways to achieve them. For this reason, theory has been indispensable in guiding complex and fractious environmental management decisions, such as with threatened species like the spotted owl and biodiversity loss caused by habitat fragmentation.

The role of theory has been less developed in other areas where, although relevant theories exist, management decisions must balance fundamental conflicts between humans and nature, such as in forest or fisheries management. While theory shows that fire can benefit forest ecosystems, the role of fire has been dramatically altered by human activities. Shifts in fire intensity have triggered sweeping policy changes to protect communities, but these pose significant risks to the integrity of ecosystems and the role fire historically played in shaping them. Other examples involve managing sustainable fisheries with policy that accounts for rapid changes in the ocean, often in places where implementing the best tools and methods may be limited by their cost and complexity. New Zealand's individual transferable quota policy, for instance, and the recovery of some halibut fisheries are promising demonstrations of theory guiding a collective dialogue among scientists, policymakers, and the public. The implementation of marine protected areas on the coast of California following the passage of the Marine Life Protection Act of 1999 is another successful melding of scientific theory and action.

Conversely, some attempts to inform management with theory are hampered when the wrong theory is used—perhaps because the theory chosen is more readily simplified into a catchy phrase that is accessible to a broad audience. The landscape change along the northern range of Yellowstone National Park, for instance, has often been described as a trophic cascade, which is memorable but technically incorrect. This has encouraged conservation of apex predators, when in fact understanding the change as an alternative stable state or a transient state explains the dynamic mix of biotic and abiotic factors that affect landscape structure.

It is important to mention that successfully bringing theory into policy conversations requires clear communication and a set of ground rules. Policymakers first need to help theoreticians understand what kind of information and guidance they need. And theoreticians must learn to communicate theory in ways that are accessible to diverse audiences, while preserving the nuances and uncertainties of the work. Both parties must work together to avoid the pitfalls that lead to misinterpretation of models and theory or their misuse in supporting predetermined political agendas. This includes honesty about uncertainty and transparency in model assumptions, and clear statements of what is unknown as well as what is known.

Darwin wrote of a "tangled bank" underlying the process of evolution by means of natural selection. Only with time have we come to realize how tangled this bank really is, reaching beyond diverse biological interactions to incorporate social structures, cultures, economics, governance, and technology. The increasingly tangled banks society will face now and in the future demand new theory to provide a foundation for integration across diverse disciplines and sectors of society.

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