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Incomplete Knowledge, Uncertainty, and Surprise

SCIENTIFIC KNOWLEDGE IS, INHERENTLY AND INEVITABLY, INCOMplete. In this chapter, I explore the role that incompleteness, uncertainty, and surprise play in the evolution of scientific thinking. Tentative hypotheses, initial findings, and problem frames offer a false sense of certainty about what we know. The greatest challenge of scientific discovery is to unlearn what we have learned and to do so systematically and continuously. Sometimes, in decision-making, we face a paradox: while attempting to employ the best evidence to make informed, authoritative decisions, we ignore the inherent incompleteness of knowledge. By focusing on the unpredictable dynamics and the uncertainty of coupled human-natural systems, I challenge the myths about stability, optimality, transferability, and adaptability that characterize urban planning. These myths are not necessarily false or true, but are instead simply incomplete. They represent partial explanations of how human-natural systems work. To face current challenges in urbanizing regions, a co-evolving paradigm may be more appropriate: a view that focuses on unpredictable dynamics in urban ecosystems and on strategies as experiments that help us to learn how cities work and evolve. I conclude the chapter by redefining the questions that can lead us in changing the planning paradigm.

The Paradox of Knowledge

It takes but a simple step beyond the familiar (our home, neighborhood, or city) to experience the incompleteness of our individual knowledge. It takes a little more imagination, however, to understand incompleteness in science. What we do not know may be both disproportionately greater than what we do know and qualitatively different from what we can expect. We cannot define or quantify what we do not know.

Why can this realization be important both in thinking about advances in scientific thinking and in framing the role of science in solving society's problems? The reason is that what we know influences the way that we think about what to look for and where to look for it. Whether or not we state it explicitly, we all have an idea of what "complete" or "perfect" knowledge should look like. This idea is often an abstraction, though, and is rarely connected to how the world actually works. At best, it is an expression of the relationship between what we need to know and a set of stated questions that such knowledge would answer. For example, it might provide a framework for compiling evidence about how cities affect ecosystem function.

But what if the questions we ask, although good ones, are incomplete? I propose that the questions we ask are strongly shaped by what we already know, and that so, too, is what we define as "unknown." To tackle such limitations, I propose a distinction between *ignorance*, defined as what we consider unknown—as Firestein (2012) discussed in his book *Ignorance*—and what I term *incomplete knowledge*. In a recent essay, the physicist Igor Teper (2014: n.p.) asked, "If the constitution of nature itself were changing in time, how would you know?" He concluded that we cannot assume that the future will resemble the past, based on past observations, without falling into what the philosopher David Hume (1777 [1748]: 115) called circular logic. Such scientific challenges have enormous implications for planning and decision-making.

Strategic decisions about the future—such as whether to invest in urban infrastructure, manage urban growth, and conserve natural resources—are based on our assessment of the past and our expectations for the future. To a certain extent, observations about the past define the "reference" and "boundary" conditions of the multidimensional space that shapes our predictive tools. How we think about the future has significant implications for the choices we make and the decision-making processes we apply. Traditional approaches to planning and management typically rely on predictions of probable futures extrapolated from trends observed in the past. But such predictions might not be adequate.

Incompleteness

Incomplete knowledge, uncertainty, and surprise all affect our decisions, and they all influence and interact with one another in their effects. Drawing a distinction among them can help us to clarify their roles and to tackle them as we make decisions. What helps us make good decisions is not having perfect knowledge, but acknowledging that we do not have it. In his book *Obliquity*, the economist John Kay (2010) suggested that in a world that we understand only imperfectly, we achieve better decisions when we approach a problem obliquely or indirectly. He noted that the problems we face are rarely completely specified and that the environment in which we tackle them contains irresolvable uncertainty. Problem-solving in an uncertain environment is an iterative process of continuous learning.

Part of the problem is that we know more than we can define or translate into formal expressions because our knowledge comes from multiple sources and because we can see to only a limited degree how our knowledge emerges from those sources. There is also a notable gap between our ability to perceive and our ability to synthesize and translate what we see into a set of rules. Often we cannot translate what we see into a reproducible decision-making model—a problem that reflects our unjustified trust in any one limited view of rationality. Though we know more and more about the important role that association plays in human cognitive processes by complementing rational thinking, our scientific and political institutions underestimate the power that this complementarity has in scientific discovery and decision-making (Scheffer 2014). The arts may be more effective in allowing us to simultaneously access multiple sources of knowledge. Art does not require us to explain the rules by which the work of art connects the dots. Instead it embraces incompleteness.

The recognition that knowledge is incomplete has several implications. First, our knowledge about our role in the environment cannot keep up with the rapid pace of the unknown impacts of our actions. Van der Leeuw et al. (2011) pointed out that the knowledge upon which we base our actions is disproportionately smaller than the unknown dimensions that our actions will affect. I suggest that part of the explanation for this mismatch is that our tools for understanding how the world works are inevitably incomplete and do not fully represent what we do know. Another part is that we cannot simultaneously access many sources of knowledge and synthesize or make sense of the multiple perceptions of what is real. Incompleteness of knowledge, however, is not the same as ignorance. Ignorance may include participation in an unconscious or deliberate action, such as ignoring a particular fact because of unintended bias or intentionally choosing to avoid it because it is inconvenient, unpleasant, or overwhelming. *Incompleteness* refers to the inevitable limitations constraining any individual or point of view as it seeks to represent the workings of the world.

Uncertainty

The future is more complex than any prediction we can make. But why? In part, this is true because of our limited ability to construct models that are accurate and/or precise enough to reflect the assumptions upon which they are built and the variability of the data that they are fed. We are adept at improving a model's accuracy and precision. Yet regardless of optimizations we achieve in our models, the future will surprise us. Again, why?

The key to a long view—to seeing beyond the near future and through the details of the present—lies in refining our capacity to connect the dots, to ask new questions, to access new sources of information, and to expand the methods of inquiry to include the imaginary. Predictive models are not based simply on what we know, but also on what we think we know. They are not only incomplete in their representations of how the world works; they also reflect our assumptions about what is missing. Their incompleteness has major implications for predictive modeling and long-term decision-making. Uncertainty is a dimension we can measure to determine the probability of a future event, but probability distributions are derived from the observed variability of known events. However, the probability of future events is not simply uncertain in a statistical sense. It is unknown. Here I do not argue that the future is unknowable. I argue that it is not completely knowable using our current knowledge and modeling processes. By assuming that we know what we do *not* know—that we know the probability distribution of given phenomena—we build models that tell us what we can predict with a given level of confidence that we cannot estimate.

In science, all predictions involve some level of uncertainty. Although the uncertainty may be great in some cases, scientists most often assume that it is quantifiable. Complex systems are inherently unpredictable, however, and thus their uncertainty cannot be completely quantified. A factor that makes models even more uncertain in coupled human-natural systems is nonstationarity, or the evolution of the parameters that define dynamics (Schindler and Hilborn 2015). In coupled human-natural systems, future dynamics depend on multiple drivers, such as population growth and climate change, that have very different degrees of uncertainty. The probability distribution of future predictions for coupled human-natural systems depends on the probability distributions of uncertain trends in such drivers and on their interactions. But since future driver distributions may be unknown, the uncertainty in such predictions cannot be calculated (Carpenter 2002).

In coupled human-natural systems, uncertainty and unpredictability can result from unexpected interactions among the driving forces and from the reflexive interactions between human behaviors and humans' anticipated knowledge of the environmental changes that may be brought about by their actions. In some cases, probabilities may be fundamentally unknowable. We cannot predict unexpected interactions among multiple uncertain driving forces, such as possible trajectories caused by interactions between uncertain climate changes and technological innovation. We do not know the probabilities of the impacts and feedbacks resulting from such interactions: the actual impact could very well fall outside the predicted probability distribution of model projections. As Steven Carpenter (2002: 2080) pointed out, "Even the uncertainties are uncertain, because we do not know the set of plausible models for the dynamics of the probability distributions."

Surprise

Thresholds are transition points between alternate states or regimes (Liu et al. 2007b). A regime shifts between alternate stable states when a controlling variable in a system reaches a threshold, modifying its dynamics and feedbacks (B. Walker and Meyers 2004). Subtle environmental change can set the stage for large, sudden, surprising, and sometimes irreversible changes in ecosystems. Regime shifts depend not only on the external perturbation that affects a system, but also on the size of the basin of attraction—a region in state space in which the system tends to remain (Holling 1973; Scheffer et al. 2001) (see figures 2.11–2.13). In systems with multiple stable states, gradually changing conditions may reduce the size of the basin of attraction around a state: what Holling (1973) defined as a loss of ecological resilience. It is typically described using the heuristic of the fate of a ball in a landscape of hills and valleys. As I represented in figure 2.11, a small perturbation or external event may be enough to cause a shift to an alternative stable state. However, this loss of resilience makes the system more fragile, in the sense that it can easily be tipped into a contrasting state by stochastic events.

Recent studies have provided empirical evidence that alternative stability domains exist in a variety of ecosystems, such as lakes, coral reefs, oceans, forests, and arid lands (Scheffer et al. 2001). B. Walker and Meyers (2004) described a database documenting thresholds in ecological and socioecological systems that drive system shifts (Resilience Alliance and Santa Fe Institute 2004). Complex feedbacks between natural and ecosystem processes and thresholds can generate regime shifts, but in coupled human-natural systems, we may not be able to see the effects that environmental change has on human function and well-being until ecological changes reach a certain threshold.

Regime shifts in ecosystems are difficult to predict (Scheffer and Carpenter 2003). However, increasing evidence shows that ecosystem dynamics become more variable prior to some regime shifts (Berglund and Gentz 2002; Brock and Carpenter 2006; Carpenter and Brock 2006). For example, by studying the variability around predictions of a simple time-series model of lake eutrophication, Carpenter and Brock found that a rising standard deviation (SD) could signal impending shifts about a decade in advance. Brock, Carpenter, and Scheffer (2006) explained how this statistical signal can occur in one-dimensional systems, and Carpenter and Brock (2006) showed that the variance component related to an impending regime shift can be separated from environmental noise using methods that require no knowledge of the mechanisms underlying that shift.

Myths and Paradoxes

As has been true for most of human history, breakthroughs in science often emerge from paradoxes and from the letting go of myths. Myths may very well be grounded in knowledge and observations, but they are only part of a much more complex story made up of knowledge and paradoxes. Paradoxes reveal assumptions and biases about how the world works, which emerge in the learning process. Tentative hypotheses and problem frames acquire false certainty and accuracy and become part of what we know, so the greatest challenge to scientific discovery is to systematically and continuously unlearn what we have learned. Unlearning is about abandoning the belief that what we have learned is accurate, complete, permanent, and transferrable.

Challenges

Interdependence between human and ecological processes in cities creates unprecedented challenges for planners and designers. At the same time, it provides them unique opportunities to build resilient cities—ones that can cope with environmental change in the long term. Some of our failures in managing complex human-ecological interactions in cities can be traced to our biases or to myths about nature. Holling (1973) told us that the ways that we view nature ultimately affect the ways that we study and understand ecosystems. Myths about how nature works lead to unverified assumptions about its processes and dynamics and then to inappropriate policies and strategies to protect and manage it. Urban designers and planners, for example, tend to assume that ecosystems are stable and that their processes and dynamics are relatively well understood. In the real world, however, ecosystems vary in time and space, and ecological change is subtle, rapid, and highly unpredictable (ibid.). To address the inherent uncertainty of coupled human-natural systems, we need to expose some common urban-planning myths.

Stability: Thresholds remain constant over time and thus are predictable.

Planners have long assumed that systems are stable: that they return to equilibrium when confronted with external disturbances. A *steady state* is a condition in which nature exists at or near a persistent equilibrium. The steady-state paradigm holds that disturbance can be controlled and that optimization is a strategy to achieve sustainable carrying capacities. Recently planners have begun to acknowledge multiple equilibria, yet they assume that thresholds between alternative states remain constant over time and system shifts are predictable.

But this isn't the case. Coupled human-natural systems may exhibit nonlinear responses to perturbations. There may be more than one stable regime. Both the position of a threshold along a driving variable and the depth of the basin of attraction can change. Resilience is a dynamic property. In coupled human-natural systems such as cities, reciprocal influences between system shifts may occur in both the ecological and the social systems (B. Walker and Meyers 2004).

A good example is the use of downscaled climate scenarios to make decisions. Climate scenarios are each based on a single emissions or climate model. Each scenario contains a set of assumptions about the trajectory of individual variables and associated uncertainties. Even when considering multiple climate scenarios, each based on different sets of assumptions, decision-makers cannot account for potential interactions among uncertain trajectories.

Optimality: There is an optimal resilient urban pattern and an optimal type of infrastructure.

The idea of optimality—that one can find the optimum among a set of alternatives given a set of conditions—is a direct consequence of the steady-state paradigm. Planners come to assume that for a given problem, an optimal solution exists. Decisions based on seeking the optimum assume that we can quantify risks. However, in the presence of irreducible uncertainties, we encounter multiple plausible futures whose relative probabilities are unknown. Decision-makers confronted with investment choices for dealing with floods or droughts, for example, are often misled by the confidence intervals associated with such predictions (Wilby et al. 2004). Although we can estimate the likelihoods (and confidence intervals) of environmental impacts given a set of assumptions, it is not likely that these assumptions will hold and that the future will turn out to resemble the "best-estimate" scenario. In fact, nonlinear rates of change and potential interactions among uncertain drivers may produce outcomes that more closely resemble outliers and low-probability events (Jones and Preston 2011; Reisinger, Wratt, and Allan 2011).

The farther into the future we look, the greater the uncertainty of our forecasts becomes—and even our levels of confidence about the magnitudes of uncertainties are likely to decrease as we gain greater understanding of the complexity of coupled human-natural systems. These facts have enormous consequences for decisions with long-term implications, since given our new understanding of risk, it might not be possible to adjust existing infrastructure or incrementally revise our responses. It may not be feasible or desirable to increase protection of existing land uses by building on infrastructure systems designed under outdated assumptions (e.g., adding height to a levee or raising the floor levels of dwellings) in response to each improvement in understanding. Robustness, rather than optimality, might be a more appropriate target for planning and decision-making under conditions of uncertainty.

Transferability: What is resilient in one region and at one scale is resilient in other regions and at other scales.

Many planning strategies are based on the assumption that what is resilient for a specific system function, at one scale and in one region, is resilient for other functions, at other scales and in other regions. In complex social-ecological systems, however, multiple regime shifts may occur in multiple biophysical (e.g., climate, hydrology, and biogeochemistry) and human (e.g., social, economic, and political) domains at multiple scales. Furthermore, in evolving systems, changes in scale influence resilience (B. Walker and Meyers 2004). Increasing the scale of urban systems may expand resilience by adding to the diversity of ecosystem types upon which they depend, but urban expansion may also increase the relative costs and impacts of maintaining urban activities on a larger scale. If planners focus on the resilience of a specific subsystem at a specific scale, that narrow view may cause the system to lose resilience on other fronts. To maintain resilience, we must focus instead on maintaining adaptive capacity and coping with uncertainty.

Adaptability: We can maintain resilience by adapting our current institutional frameworks.

Human and natural systems have evolved through change, adaptation, and extinction but are studied by researchers in separate domains. As a result, we do not fully understand how *coupled* human-natural systems evolve and what the limits of their adaptability might be. Furthermore, as novel functions and dynamics emerge in urban coupled human-natural systems, we may have to rethink both resilience and the way that we frame regime shifts. Emerging system functions may require transformation, which implies a regime shift toward a new desirable state, not simply adaptation.

Adaptation planners assume that we can maintain resilience by adapting our current institutional frameworks. Yet just as we cannot simply adjust or upgrade existing infrastructure to deal with flooding and other climate changes (by, e.g., strengthening flood-control structures), existing institutional settings may need to be reinvented by revising traditional assumptions of problem-solving from top-down control to self-organization. The theory of complex systems provides a solid foundation for testing hypotheses about system properties (e.g., self-organization) that enable coupled human-natural systems to change their internal structure to adapt and evolve in response to external circumstances. To create a co-evolving paradigm, we may have to reconfigure current planning frameworks and fundamentally transform our current institutions for managing cities.

Planning under Uncertainty

At the core of the challenges faced by cities across the world lies our inevitable uncertainty about global environmental change. Not only are extreme events uncertain; so, too, is the very measure of that uncertainty (e.g., the tails of the probability distributions).

Under uncertainty, each problem has more than one solution, and solutions may change with time as conditions evolve and as our perceptions and understanding change. New viewpoints may emerge as we see and formulate tentative solutions. Uncovering a new viewpoint often exposes new opportunities and unexplored resources for problem-solving.

Redefining Our Questions

If uncertainty and surprise are fundamental elements in decision-making, perhaps we have been asking the wrong question:

> How can we minimize uncertainty about future changes in order
> to select the most optimal strategies for controlling them?

A more effective question may be:

> How can we characterize uncertainty about future changes in order
> to inform development of the most robust strategies for planning?

The assumption of traditional planning is that we could achieve a perfect decision if we could

- eliminate uncertainty,
- remove differences,
- have complete knowledge,
- have plenty of resources, and
- achieve perfect coordination.

But probably under such conditions, there would be no need to make a complex decision, as only one logical course would exist. In the face of uncertainty, we need to revise these assumptions. We will have to

- embrace uncertainty to build robust decisions,
- build on differences to explore opportunities,
- use information to test what we know,
- manage resources effectively to maximize benefits, and
- transform redundancy into partnership.

This view focuses not only on unpredictable dynamics in ecosystems, but also on institutional and political flexibility. We need to reconfigure our problem-solving strategies. Instead of seeking to reduce uncertainty, decision-makers should aim to identify robust strategies that will be appropriate under a broad range of alternative futures.

Direct experience of the dramatic shift in extreme climate-event probability across cities worldwide has significantly influenced how decision-makers perceive and assess risk. New York City's response to Hurricane Sandy is only one of many examples of emerging efforts to fully integrate uncertainty into local decision-making by redefining "extreme" events as "normal" ones. Such a change in perspective calls for what Rosenzweig and Solecki (2014) described as achieving a meaningful nonstationary public policy and institutionalizing climate-change adaptation and resiliency.

Future policies and management practices in urbanizing regions will succeed or fail based on their ability to acknowledge and address the complexities and uncertainties of coupled human-natural systems. When policies aim to stabilize an ecological system or eliminate its variability, the inevitable outcome is collapse (Carpenter and Gunderson 2001). This is where scenario-building can be a valuable process: it allows decision-makers to explore possible futures and account for uncertainty and surprise.

Uncertainty and Planning across Time and Space

The relationship between uncertainty and decision-making is complex. There are many sources and varieties of uncertainty and many diverse types of decisions. Not all aspects of uncertainty are untreatable. In fact, several of the important variables driving change can be foreseen on a relatively short time scale. Even some aspects of complex phenomena such as climate change have a relatively limited degree of uncertainty compared to less predictable elements of the same phenomena and thus pose different challenges in decision-making. It is also important to discriminate among different kinds of uncertainty. Consider, for example, the difference between the uncertainty that arises due to limited scientific understanding and or/agreement on the many feedbacks governing how the Earth's systems operate and the uncertainty of predictions caused by imperfect climate modeling that is based on universally accepted scientific bases. We must also distinguish between scientific uncertainty and disagreement regarding the timing of appropriate mitigation efforts.

Cross-scale interactions among variables governing the dynamics of coupled human-natural systems add further dimensions of uncertainty.

Both human and natural processes operate and affect each other at multiple temporal and spatial scales. What is resilient at the local scale over a short time period might not be resilient at regional or global scales over the long term (Carpenter et al. 2001). Trade-offs among system functions, thresholds, and tipping points vary across scales, and tele-connections (rural-urban, local-global, and across cities) imply that change and adaptation also operate across scales.

Human civilization is characterized by an increasing capacity to subsidize resources across time and space. Technological development associated with urbanization and agricultural transitions has expanded human ability to maintain system stability (e.g., grow food or supply water) in one place and time scale at the expense of other places and longer time scales. Yet after a certain threshold in the supporting ecosystem is crossed, system resilience is compromised (Carpenter et al. 2001). Using the Dutch Deltaworks Program as an example, Chelleri et al. (2015) show that the evolution of flooding infrastructure reflects different phases of multiple approaches to achieving resilience. Overlap between adaptation and transformation perspectives suggests that multidimensional resilience strategies are essential when dealing with regime shifts.

Similarly, there are very different levels of complexity and scales of decisions. Stafford Smith et al. (2011) proposed that we classify decisions according to their lifetime, their incremental or transformational nature, and their scale. Decisions may have a short lead time and short-term consequences or a short lead time and long-term consequences (e.g., whether to build infrastructure or develop land). It is possible to reduce complexity and uncertainty by identifying interactions among a decision's lifetime, the type of uncertainty in the relevant drivers of change, and the nature of the options for responding to adaptation. Decisions with a short time scale can rely on predictive models, which can produce relatively accurate future scenarios. Decisions with longer lifetimes must deal with potentially wider arrays of possible futures—and that may require integrating a diversity of approaches.

Rethinking planning in a time of rapid planetary change requires that planners understand the implications of incomplete knowledge, uncertainty, and surprise in decision-making and formulate strategies that vary and evolve across time and space.