

# Limits of prediction in modeling social systems\*

Andrew Bell<sup>†</sup>

Daniel H. Neilson<sup>‡</sup>

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## 1 Introduction

Several recent popular science books have discussed the limitations of predictive modeling in natural and social environments. Pilkey and Pilkey-Jarvis (2007) cite numerous applications of models to natural systems—estimating the maximum sustainable yield in the North Atlantic cod fishery, the rate of sand loss in engineered beaches throughout the United States, or the time to failure of nuclear containment units in Yucca Mountain, among others. Orrell (2007) explores the human desire to predict wealth, health, and the weather from the role of circles in the models of planetary orbits in ancient Greece through to the general circulation models of climate in the present day. In both books, the authors try to outline the limits we face in trying to predict the future.

In this paper we contribute to this discussion by formalizing the limits of prediction in social models by reference to the adaptive cycle metaphor of Holling (2001) and Gunderson and Holling (2001). In their metaphor, adaptive systems follow a cycle of growth, conservation, collapse, and reorganization; in the reorganization phase, the new trajectory of growth is both constrained by “larger” or more slowly changing systems, and influenced by “smaller” or more quickly changing systems. We argue that the time scale of interest in many social phenomena requires us to include this reorganization phase in our analysis. Since it is not generally possible to include the set of underlying cycles in a model, neither is it possible to predict *a priori* which among these cycles will emerge as dominant processes in the system of interest. The modeling of systems in which the time scale of interest includes the reorganization phase of the adaptive cycle thus requires that significant assumptions about the dominant processes be designed into the model.

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<sup>†</sup>School of Natural Resources and the Environment, University of Michigan

<sup>‡</sup>Department of Economics, Columbia University

## 2 Systems, Panarchy, and Adaptive Cycles

In this article we use the term “system” to mean a description of a process, idea, or physical thing at multiple scales. This description includes a large set of elements and concepts characterized by different scales (molecules, trees and animals, forests and cities, planets, and so on) and connections, or relationships, among them (molecules forming bodies, trees and animals forming a forest, ecosystems shaping the climate and in turn, the climate reshaping ecosystems). Within a system, sub-sets of elements at a particular scale are generally more densely connected to one another than to other elements, and form distinct subsystems. In some cases, such as for living beings, the changes that occur in these sub-systems follow what Gunderson and Holling (2001) call adaptive cycles, with continual processes of growth, collapse, and renewal. In their discussion of adaptive cycles Gunderson and Holling (2001) coin the term “panarchy” to describe the interactions among cycles of different scales within a system. In contrast to a hierarchy, where larger, more powerful entities strictly control entities operating at smaller scales, panarchy implies influence among sub-cycles both from the top down and the bottom up. In the context of a large system, this means that larger, slow-moving cycles (like climate) exert a downward influence on ecosystems, and in turn on the individual flora and fauna that comprise them. At the same time, the individual trees and animals (small, fast-moving cycles) exert an upward influence on the growth of the ecosystem, which in turn impacts climate.

At each level, Gunderson and Holling identify three axes along which to measure the subsystem that operates at that level—potential, controllability, and adaptive capacity. Potential is the “wealth” of the subsystem, which enables it to produce and function. Controllability is the density of internal connections among elements of the subsystem. Greater controllability allows it to function more efficiently at the cost of greater rigidity. This is captured along the third dimension, referred to alternately by the negative *rigidity* and the neutral *adaptive capacity*, which measures the ability of the subsystem to react to external shocks. Holling posits cyclical dynamics within each subsystem.

Gunderson and Holling approach this metaphor from the viewpoint of ecology, their area of expertise. In ecology, the process by which new ecosystem niches are exploited has been well-studied. Two phases characterize this process, *exploitation* and *conservation*. The adaptive cycle adds two new phases which reflect the ongoing creative destruction which such systems exhibit. As the conservation stage matures, resources are more effectively exploited through increased specialization and denser interconnections within the system. This comes at the cost of increased rigidity, which leads to susceptibility to disturbances from smaller, faster subsystems. Eventually, these disturbances overwhelm the inflexible system, leading to the *release* phase, in which resources are freed from the rigid but efficient system of exploitation which had prevailed. Finally, the released resources begin to *reorganize* as new processes become able to exploit them under the new conditions.

As has already been suggested, subsystems at different levels of the panarchy influence each other. Gunderson and Holling identify two modes of influence, one acting upward and the other downward. The upward effect, *revolt*, refers to the ability of structural change in a subsystem to effect change in its containing supersystem. As noted, this is likely when the subsystem is in the reorganization phase, when existing elements are being reorganized into new systems. The higher is the rigidity of the containing system, the more likely it is to be destabilized by changes in the subsystem, forcing a reorganization around new principles. The downward effect Gunderson and Holling refer to as *remember*. This denotes the stabilizing effect that larger, slower-moving systems have on smaller, faster-moving subsystems. Faster-moving systems operate with the conditions of slower-moving systems at the stable conservation stage of the adaptive cycle taken as given—the revolt effect is unlikely to destabilize the slower system, so its state constrains the faster one.

On the basis of these concepts, we return to our central question, understanding the limitations of modeling social systems. At the conservation phase the subsystem is increasingly stable and rigid. Here, the dominant causal relations among elements of the subsystem are fixed and unchanging, and the subsystem is amenable to analysis. At other phases, the dominant inter-agent relations may be

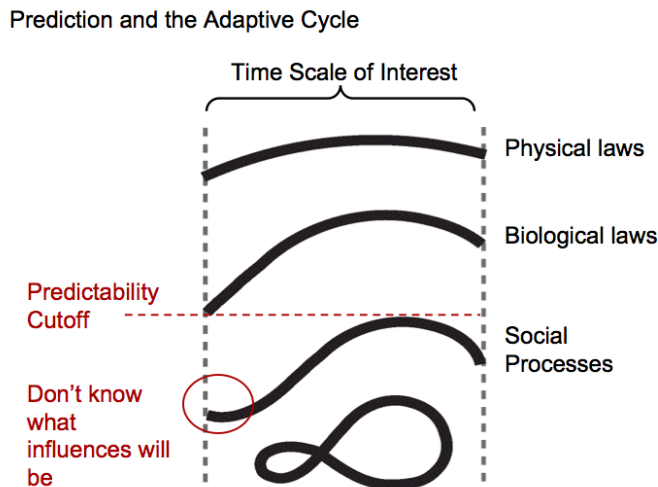


Figure 1: The predictability cutoff.

in flux, due to internal shocks or to influence from higher or lower levels. In the  $\alpha$  phase, for example, where potential is high and rigidity and controllability are low, it may be impossible to determine which organizing process or effect will turn out to dominate. Only once the system has begun its transition to the  $K$  phase, which is to say once organizing processes have been established, can a useful predictive model be made.

### 3 Implications for prediction

For many of the social systems we wish to model—the emergence of norms in societies, of leading products in markets—the time scale of interest includes the reorganization and exploitation phases of the adaptive cycle. The emergence of norms for the governance of a resource, for example, occurs as different innovative ideas and practices, constrained from above by larger social and cultural rules, as well as climate and geography, are tested against each other (the reorganization phase). Eventually, a subset of these will emerge to become the norms and rules for governing the resource of interest (the exploitation phase).

However, it is generally not possible to model what comprises the set of underlying “smaller” adaptive cycles that influence the trajectory followed in the exploitation phase. In the resource governance example, these smaller cycles can be thought of as the practices and efforts of individuals or smaller groups within the resource community, as well as other important local factors—weather events like floods and droughts, for example. Their effects on resource governance are innovations coming from local stakeholders, or extreme weather events. It is difficult to account for the set of all such smaller cycles that are relevant to a particular system as it would require generating a set of all possible ideas, practices, and environmental events, among other things. It is thus difficult to understand how they will interact to form the eventual emergent set of rules. It follows that it is not generally possible to predict the trajectory of the exploitation phase before it has actually begun. Describing the failure of the sophisticated GARCH econometric model to predict the Mexican peso crisis of 1994–95 (a trajectory), Orrell (2007) quips, “there is no parameter for peasant uprising.” It

is not reasonable to expect of models of complex systems like communities and economies to include the set of all possible innovations or events that can influence their trajectories.

This implies a cutoff for predictability in social models (see Figure 1). For many modeling efforts, the time scale of interest captures systems in their conservation phase. Physical rules certainly have not changed in recorded history, nor do we expect them to (though perhaps they might, someday). Accordingly, we are able in a wide range of physical systems to create models that predict well the properties we are interested in. In other domains, the time scale of interest captures large portions of the exploitation phase of a system of interest. Paleontological records allow us to study the trajectories taken by different phenotypes of living creatures, after the subset of candidate creatures had emerged.

However, as we move down into more rapidly changing systems—ecosystems and economies, for example—modeling becomes more difficult and we are required to build a significant amount of structure into models to make them useful. In ecosystems, we are not capable of predicting the outcomes of succession in general, and must pursue different scenarios, in which different subsets of candidate species we have chosen compete to succeed. The same is true for models of many social processes. Payoff and sanctioning structure must be designed into models of institutional development, functional form must be designed into econometric analysis—in general, social models are restricted to answering “what if” questions based on assumptions about the processes that will begin to dominate, or modeling of exploitative trajectories once the dominant processes have emerged.

This limitation is fairly commonly acknowledged in some areas, particularly in the use of agent-based models where emergence of patterns from agent interaction is highly dependent on the rules selected for agent behavior and other model assumptions. The goal of this paper is to formalize the limitation as a general consequence of the presence of an uncertain reorganization and exploitation phase within the time scale of interest in many social problems.

## 4 Examples

In Table 1, we present some examples from the social-science literature that illustrate the above points. The well-known growth model of neoclassical economics, due to Solow (1957) and Swan (1956), is particularly relevant. This class of models explains macroeconomic growth as a consequence of technological change. If we view technology as an adaptive cycle, the issue with the model becomes clear. The characteristic time scale of technological change is on the order of years or decades. Thus the cycle will, over the time relevant for economic growth, pass repeatedly through its reorganization phase. Necessarily, then, these theorists assumed a particular process for the single most important force driving growth in their models.

The problem of stock-option valuation provides a different sort of example. MacKenzie and Millo (2003) demonstrated that, rather than describing a pre-existing reality, the theory of option pricing put forth by Black and Scholes (1973) and Merton (1973) itself *created* a market in which it was a good description of reality. To tie this to the present argument, consider the market for stock options and its associated theories and methods to be an adaptive cycle. In 1973, at the establishment of the Chicago Board Options Exchange (CBOE), there was no generally accepted theory of option pricing, and as MacKenzie and Millo argue, the exchange’s culture actively shunned such theory. But as option trades came to be greater in volume and complexity, a theory was needed for purposes of risk management and hedge design. The theory of Black and Scholes (1973) and Merton (1973) came to fulfill that role, and from the late 1970s until 1987 the model indeed explained prices very well. Following the stock-market crash of October 1987, options traders began to price in a greater probability of extreme loss, and since then the Black–Scholes model has performed more poorly.

This example corresponds with the main features of the adaptive cycle we have been discussing. The predictive Black–Scholes model functioned poorly in the (re)organization phase of the CBOE,

Citation	Problem	Model design	Analysis
Solow (1957)	Neoclassical growth	Aggregate macro model with exogenous technological change and population growth	The model concludes that changes in technology drive growth, but these are outside of the model and assumed exogenous. This is unavoidable, since technological change occurs at a rapid time scale with respect to our range of observation.
Black and Scholes (1973); Merton (1973); MacKenzie and Millo (2003)	Stock-option valuation	Log-normal returns; investors free to buy stock with borrowed funds; no transaction costs	In this case, rather than finding empirical regularity in the prices of stock options, Black and Scholes (1973) and Merton (1973) created a theory which became true as market participants adopted it as a pricing tool. Theorizing about a social adaptive cycle still in its $\alpha$ phase is difficult as the process can change in response to the theory. 1987 crash
Ostrom (1990); Taylor (1987)	Norms for managing common-property resources	Game-theoretic approaches (Prisoner's Dilemma/Assurance Games) to evaluate individual payoffs	Each "norm"—an agreement to monitor, sanction, or consume—must be designed into the model. Rather than evolve solutions to CPR problems, the model is only able to compare strengths of particular designed solutions

Table 1: Examples.

then did better during the exploitation phase, then failed as the system reorganized itself. Moreover, the example illustrates an evolutionary process by which causal relations can come to be established where they had been absent before. The Black–Scholes model provided structure where one was needed, and became more true as reality bent itself to the model.

Resource management problems are another area where predictability is desired. Ostrom (1990) has made extensive use of game theory and games based on the Prisoner’s Dilemma to explore possibilities for the management of common property resource (CPR) problems. She extends the structure of the basic Prisoner’s Dilemma to include a “contract” clause, whereby an additional layer of decisions is added to the game in which both players can agree to a binding contract on how to use the resource in question. When both players agree to the contract, it becomes a mechanism for sustainable resource use and higher payoffs within the game. Axelrod (1986) has explored similar extensions to the Prisoner’s Dilemma, with opportunities for players to sanction those who defect, and thus create incentives for players to make more sustainable use of the shared resource. Axelrod extends this idea even further, to allow players to sanction those who fail to sanction defectors, a meta-sanctioning mechanism, resulting in further gains to the community.

All of these ideas represent specific innovations that might be chosen by a community seeking to develop governing mechanisms for shared resources, but they are by no means exhaustive sets of options, nor inevitable outcomes. Many communities fail to find successful modes of governance for their resources, and those that do often need to develop intricate, context-specific rules. Ostrom (1990) describes a group of fishers whose successful set of rules for maintaining the health of their fishery include an exclusive co-operative of fishers, a lottery for fishing locations, and mandatory migration of fishers through the locations as the fish move in order to let all fishers have opportunities at the best spots. Real rules for sustainable resource management are complicated, and beyond the capability of a model to search out and find on its own.

As paradigms for resource management crumble and are replaced by new norms and sets of rules, they are constrained by social and cultural structures (the big, slow adaptive cycles) and influenced by new ideas and possibilities for management (the small, fast adaptive cycles). As in the example of the fishers, the innovations that emerge to form the new rules are complicated, and often approached through a long trial-and-error process. The game-theoretic approach to modeling resource-use decisions has no mechanism for such a trial-and-error exploration of alternatives, nor a mechanism for generating alternatives. Instead, it is restricted to testing the consequences of particular innovations, which may or may not emerge in real systems.

## 5 Conclusion

In this article, we have sought to understand why some phenomena, in particular those of the social domain, are resistant to precise predictive modeling. We have employed the adaptive cycle metaphor of Gunderson and Holling (2001), developed from ecology but applicable to many dynamic complex systems. Social processes often enter the reorganization phase of the cycle during the relevant time scale, and during this phase systems are susceptible to disturbances from faster-moving cycles. As a result, the predictability of a cycle is limited to a time scale not including its reorganization phase.

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