System Dynamics Modeling:

TOOLS FOR LEARNING IN A COMPLEX WORLD

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A ccelerating change is transforming our world, from the prosaic (such as the effect of information technology on the way we use the telephone) to the profound (such as the effect of greenhouse gases on the global climate). Some of these changes amaze and delight us; others impoverish the human spirit and threaten our survival. More important, thoughtful leaders increasingly suspect that the tools they have been using have not only failed to solve the persistent problems they face, but may in fact be causing them. All too often, well-intentioned efforts to solve pressing problems create unanticipated side effects. Our decisions provoke unforeseen reactions. The result is *policy resistance*, the tendency for interventions to be defeated by the response of the system to the intervention itself. From California's failed electricity reforms, to road building programs that create suburban sprawl and actually increase traffic congestion, to the latest failed change initiative in your company, our best efforts to solve problems often make them worse. Table 1 lists some examples, including economic, social, and environmental issues.

While we like to imagine that new technologies and accelerating change present us with new and unique challenges, policy resistance is nothing new. In 1516, Sir Thomas More wrote in *Utopia* about the problems of policymaking, saying "And it will fall out as in a complication of diseases, that by applying a remedy to one sore, you will provoke another; and that which removes the one ill symptom produces others." The late biologist and essayist Lewis Thomas, in an essay entitled "On Meddling," provided both a diagnosis and a solution:

> When you are confronted by any complex social system, such as an urban center or a hamster, with things about it that you're dissatisfied with and anxious to fix, you cannot just step in and set about fixing with much hope of helping. This realization is one of the sore discouragements of our century . . . You cannot

TABLE 1.   Examples of Policy Resistance

- California's partial deregulation of the electricity market, touted as a way to lower costs to consumers, has led to record rates, rolling blackouts, and economic and political turmoil.

- The United States spends more on health care than any other nation in the world (both total and as a fraction of GDP), yet more than 40 million people have no health care coverage, and the U.S. lags behind most other developed nations in life expectancy and infant mortality.

- "Use of Cheaper Drugs Pushes Costs Up, Not Down, Study Finds: Limiting what is prescribed, as managed-care systems do, has unintended effect of increasing costs, results show." (Headline in *LA Times*, 3/20/96, reporting Univ. of Utah study of 13,000 patients in various HMOs)

- Low tar and nicotine cigarettes actually increase intake of carcinogens and carbon monoxide as smokers compensate for the low nicotine content by smoking more cigarettes per day, by taking longer, more frequent drags, and by holding the smoke in their lungs longer.

- Road building programs designed to reduce congestion have increased traffic, delays, sprawl, and pollution.

- Despite widespread use of labor-saving appliances, Americans have less leisure today than 50 years ago.

- The U.S. government's war on drugs, focusing on interdiction and supply disruption (particularly cocaine production in South America), with a cost of billions per year, has had only a small impact on cocaine cultivation, production, or smuggling. Drug use in America and elsewhere remains high.

- The U.S. policy of fire suppression has increased the number and severity of forest fires. Rather than frequent, small fires, fire suppression leads to the accumulation of dead wood and other fuels leading to larger, hotter, and more dangerous fires, often consuming the oldest and largest trees, which previously survived smaller fires unharmed.

- Flood control efforts such as levee and dam construction have led to more severe floods by preventing the natural dissipation of excess water in flood plains. The cost of flood damage has increased as the flood plains were developed by people who believed they were safe.

- Imposing 200-mile territorial limits and fishing quotas to protect fish stocks did not prevent the collapse of the George's Bank fishery off the coast of North America. Once the world's richest, by the mid-1990s many species were commercially extinct, the fishery was shut down, the fleets were idled, and the local economies were in depression.

- Deregulation of the U.S. Savings and Loan industry, designed to save the industry from financial problems, led to a wave of speculation followed by collapse, at a cost to taxpayers in the hundreds of billions of dollars.

- Antiretroviral drugs have been a literal lifesaver for people living with HIV, if they can afford them. However, the drop in mortality has led to a reduction in the perceived risks of the virus. In some communities, people are engaging in more risky behaviors and are less vigilant about safe practices, and the incidence of new cases of HIV infection, after years of decline, is rising.

- Antibiotics have stimulated the evolution of drug-resistant pathogens, including virulent strains of TB, strep, staph, and sexually transmitted diseases. Pesticides and herbicides have stimulated the evolution of resistant pests and weeds, have killed off natural predators, and have accumulated up the food chain to poison fish, birds, and, sometimes, humans.

> meddle with one part of a complex system from the outside without the almost certain risk of setting off disastrous events that you hadn't counted on in other, remote parts. If you want to fix something you are first obliged to understand . . . the whole system. . . . Intervening is a way of causing trouble.[1]

However, how can one come to understand the whole system? How does policy resistance arise? How can we learn to avoid it, to find the high-leverage policies that can produce sustainable benefit?

For many, the solution lies in *systems thinking*—the ability to see the world as a complex system, in which we understand that "you can't do just one thing"

and that "everything is connected to everything else." With a holistic worldview, it is argued, we would be able to learn faster and more effectively, identify the high leverage points in systems, and avoid policy resistance. A systemic perspective would enable us to make decisions consistent with our long-term best interests and the long-term best interests of the system as a whole.[2]

The challenge facing us all is how to move past slogans about accelerating learning and systems thinking to useful tools that help us understand complexity, design better operating policies, and guide effective change. System dynamics is a method to enhance learning in complex systems. Just as an airline uses flight simulators to help pilots learn, system dynamics is, partly, a method for developing management flight simulators (often based on formal mathematical models and computer simulations) to help us learn about dynamic complexity, understand the sources of policy resistance, and design more effective policies.

However, successful intervention in complex dynamic systems requires more than technical tools and mathematical models. System dynamics is fundamentally interdisciplinary. Because we are concerned with the behavior of complex systems, system dynamics is grounded in the theory of nonlinear dynamics and feedback control developed in mathematics, physics, and engineering. Because we apply these tools to the behavior of human as well as technical systems, system dynamics draws on cognitive and social psychology, organization theory, economics, and other social sciences. To solve important real world problems, we must learn how to work effectively with groups of busy policymakers and how to catalyze change in organizations.

To introduce this special section on system dynamics, I briefly discuss how policy resistance arises from the mismatch between the dynamic complexity of the systems we have created and our cognitive capacity to understand that complexity. I then summarize the system dynamics approach, illustrate some tools, and discuss some of the limitations and pitfalls. Finally, I summarize the applications discussed in the articles in this special section. Readers interested in learning more about system dynamics and about successful applications should refer to the growing scholarly and practitioner literature.[3]

Dynamic Complexity

Policy resistance arises because, as wonderful as the human mind is, the complexity of the world dwarfs our understanding.[4] Our mental models are limited, internally inconsistent, and unreliable. Our ability to understand the unfolding impacts of our decisions is poor. We take actions that make sense from our short-term and parochial perspectives, but due to our imperfect appreciation of complexity, these decisions often return to hurt us in the long run. To understand the sources of policy resistance, we must therefore understand both the complexity of systems and the mental models that we use to make decisions.

Most people think of complexity in terms of the number of components in a system or the number of possibilities one must consider in making a decision. The problem of optimally scheduling an airline's flights and crews is highly complex, but the complexity lies in finding the best solution out of an astronomical number of possibilities. Such problems have high levels of *combinatorial* complexity. However, most cases of policy resistance arise from *dynamic complexity*—the often counterintuitive behavior of complex systems that arises from the interactions of the agents over time. Dynamic complexity can arise even in simple systems with low combinatorial complexity. For example, courses in system dynamics often begin with the "Beer Distribution Game," a role-playing board game simulation representing a manufacturing supply chain.[5] The game is highly simplified—there is only one SKU, not tens of thousands. Each player has exactly one customer and one supplier. Yet players consistently generate wild fluctuations in production and inventory, and average costs are ten times greater than optimal. Complex and dysfunctional dynamics arise from a game you can play on your dining room table and whose rules can be learned in 15 minutes.

Table 2 describes some of the characteristics of complex dynamic systems. These attributes are common, but counterintuitive. Where the world is dynamic, evolving, and interconnected, we tend to make decisions using mental models that are static, narrow, and reductionist. Among the elements of dynamic complexity people find most problematic are feedback, time delays, stocks and flows (accumulations), and nonlinearity.

Feedback

One cause of policy resistance is our tendency to interpret experience as a series of events, for example, "inventory is too high," or "sales fell last month." Accounts of who did what to whom are the most common mode of discourse, from the mailroom to the boardroom, from the headlines to the history books. We are taught from an early age that every event has a cause, which in turn is an effect of some still earlier cause: "Inventory is too high because sales unexpectedly fell. Sales fell because the competitors lowered their price. The competitors lowered their price because . . ." Such event-level explanations can be extended indefinitely. They allow us to blame others for our difficulties, but also, as a consequence, reinforce the belief that we are powerless.

The event-oriented, open-loop worldview leads to an event-oriented, reactionary approach to problem solving (Figure 1). We assess the state of affairs and compare it to our goals. The gap between the situation we desire and the situation we perceive defines our problem. For example, suppose your firm's profits fall below Wall Street expectations. You need to boost profits, or you'll be searching for a new job. You consider various courses of action, select the options you deem best, and implement them. You might initiate various process improvement programs to boost productivity, increase the number of new products in the development pipeline to boost sales, and announce a round of layoffs to cut expenses. Your consultants, spreadsheets, and pro forma analyses suggest

TABLE 2. Dynamic Complexity

Dynamic Complexity **Arises Because Systems Are:**

- **Constantly Changing:** Heraclitus said, "All is change." What appears to be unchanging is, over a longer time horizon, seen to vary. Change in systems occurs at many time scales, and these different scales sometimes interact. A star evolves over billions of years as it burns its hydrogen fuel, then can explode as a supernova in seconds. Bull markets can go on for years, then crash in a matter of hours.

- **Tightly Coupled:** The actors in the system interact strongly with one another and with the natural world. Everything is connected to everything else. As a famous bumper sticker from the 1960s proclaimed, "You can't do just one thing."

- **Governed by Feedback:** Because of the tight couplings among actors, our actions feed back on themselves. Our decisions alter the state of the world, causing changes in nature and triggering others to act, thus giving rise to a new situation which then influences our next decisions. Dynamics arise from these feedbacks.

- **Nonlinear:** Effect is rarely proportional to cause, and what happens locally in a system (near the current operating point) often does not apply in distant regions (other states of the system). Nonlinearity often arises from the basic physics of systems: Insufficient inventory may cause you to boost production, but production can never fall below zero no matter how much excess inventory you have. Nonlinearity also arises as multiple factors interact in decision making: Pressure from the boss for greater achievement increases your motivation and effort—up to the point where you perceive the goal to be impossible. Frustration then dominates motivation—and you give up or get a new boss.

- **History-Dependent:** Taking one road often precludes taking others and determines where you end up (path dependence). Many actions are irreversible: You can't unscramble an egg (the second law of thermodynamics). Stocks and flows (accumulations) and long time delays often mean doing and undoing have fundamentally different time constants: During the 50 years of the Cold War arms race the nuclear nations created more than 250 tons of weapons-grade plutonium (^{239}Pu). The half life of ^{239}Pu is about 24,000 years.

- **Self-Organizing:** The dynamics of systems arise spontaneously from their internal structure. Often, small, random perturbations are amplified and molded by the feedback structure, generating patterns in space and time and creating path dependence. The pattern of stripes on a zebra, the rhythmic contraction of your heart, the persistent cycles in the real estate market, and structures such as sea shells and markets all emerge spontaneously from the feedbacks among the agents and elements of the system.

- **Adaptive:** The capabilities and decision rules of the agents in complex systems change over time. Evolution leads to selection and proliferation of some agents while others become extinct. Adaptation also occurs as people learn from experience, especially as they learn new ways to achieve their goals in the face of obstacles. Learning is not always beneficial, however.

- **Characterized by Trade-Offs:** Time delays in feedback channels mean the long-run response of a system to an intervention is often different from its short-run response. High leverage policies often cause worse-before-better behavior, while low leverage policies often generate transitory improvement before the problem grows worse.

- **Counterintuitive:** In complex systems cause and effect are distant in time and space while we tend to look for causes near the events we seek to explain. Our attention is drawn to the symptoms of difficulty rather than the underlying cause. High leverage policies are often not obvious.

- **Policy Resistant:** The complexity of the systems in which we are embedded overwhelms our ability to understand them. The result: Many seemingly obvious solutions to problems fail or actually worsen the situation.

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these decisions will restore growth and profitability. The consultants move on, and you turn to other pressing issues. Problem solved—or so it seems.

Contrary to the sequential, open-loop view in Figure 1, real systems react to our interventions. There is feedback: The results of our actions define the situation we face in the future. The new situation alters our assessment of the problem and the decisions we take tomorrow (see the top of Figure 2).

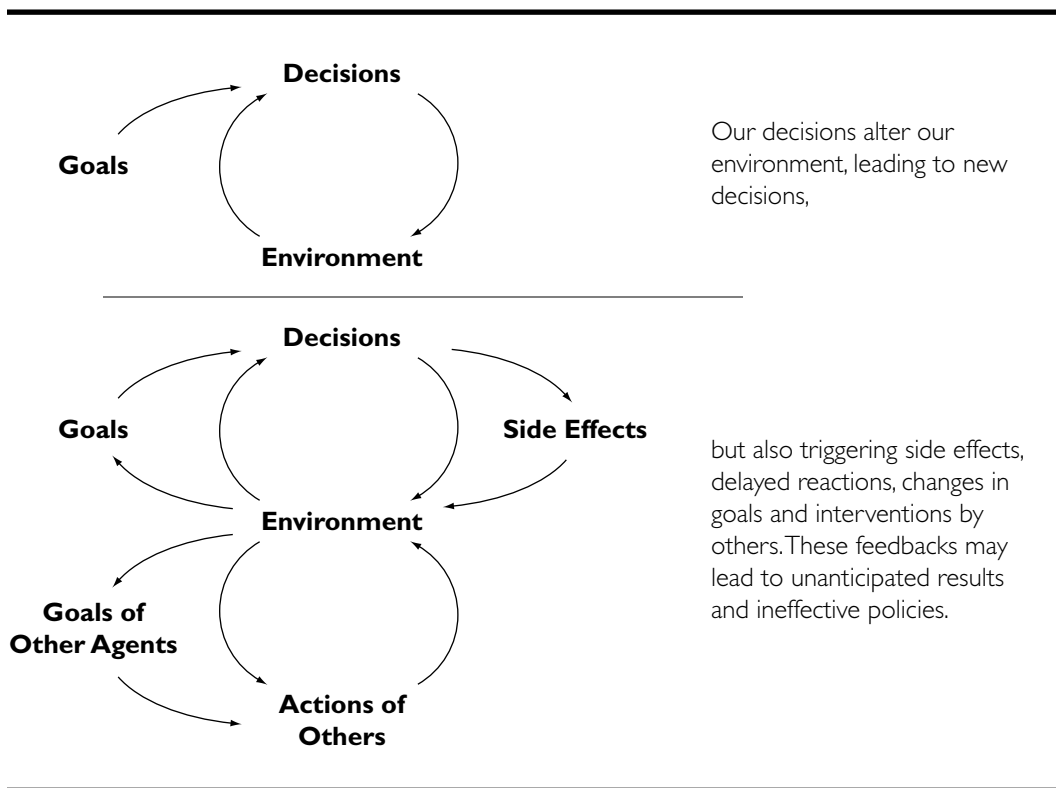**FIGURE 1.** Event-Oriented View of the World

Moreover, as shown in the bottom of Figure 2, our actions may also trigger side effects we didn't anticipate. Other agents, seeking to achieve their goals, react to restore the balance we have upset. Policy resistance arises because we do not understand the full range of feedbacks operating in the system. For example, the improvement initiatives you mandated never got off the ground because layoffs destroyed morale and increased the workload for the remaining employees. New products were rushed to market before all the bugs were worked out, so now warranty claims explode while sales slump. Rising customer complaints overwhelm your call centers and service organization. Stressed by long hours, budget cuts, and continual crisis, your best engineers and most experienced managers quit to take better jobs with your competitors. Yesterday's solutions become today's problems. Without an understanding of the feedback processes that create these outcomes as a consequence of our own decisions, we are likely to see these new crises as more evidence confirming our view that the world is unpredictable, unpleasant, and uncontrollable—that all we can do is react to events.

Time Delays

Time delays between taking a decision and its effects on the state of the system are common and particularly troublesome. Delays in feedback loops create instability and increase the tendency of systems to oscillate. As a result, decision makers often continue to intervene to correct apparent discrepancies between the desired and actual state of the system long after sufficient corrective actions have been taken to restore the system to equilibrium. Research shows convincingly that people commonly ignore time delays, even when the existence and contents of the delays are known and reported to them, leading to overshoot and instability.[6]

More subtly, delays reduce our ability to accumulate experience, test hypotheses, and learn. A 1988 study estimated the improvement half-life in a wide range of firms. The improvement half-life is the time required to cut the defects generated by a process in half. Improvement half-lives were as short as a few months for simple processes with short cycle times (for example, reducing operator error in a job shop) while complex processes with long cycle times (such as product development) had improvement half lives of several years or more.[7]

FIGURE 2. The Feedback View of the World

Our decisions alter our environment, leading to new decisions,

but also triggering side effects, delayed reactions, changes in goals and interventions by others. These feedbacks may lead to unanticipated results and ineffective policies.

Stocks and Flows

Stocks and flows—the accumulation and dispersal of resources—are central to the dynamics of complex systems. A population is increased by births and decreased by deaths. A firm's inventory is increased by production and decreased by shipments, spoilage, and shrinkage. It is only in the past decade or so that the strategic management community has begun to consider the role of stocks and flows explicitly, as the resource-based view of the firm has grown in popularity. The resource-based view expanded the definition of a firm's resources beyond tangible stocks such plant, equipment, cash, and other traditional balance sheet items to include less obvious but more important stocks underlying firm capabilities, such as employee skills, customer loyalty, and other forms of intangible human, social, and political capital.[8]

Nevertheless, research shows that people's intuitive understanding of stocks and flows is poor. Figure 3 illustrates the problem with one of the simplest stock-flow structures: a bathtub. The stock of water in the tub is filled by the inflow and drained by the outflow. From the graphs of the flows it is easy to infer the trajectory of the stock, and without use of calculus or any mathematics beyond simple arithmetic. However, the average performance of graduate students at an elite business school was only 46%. In this and related stock-flow
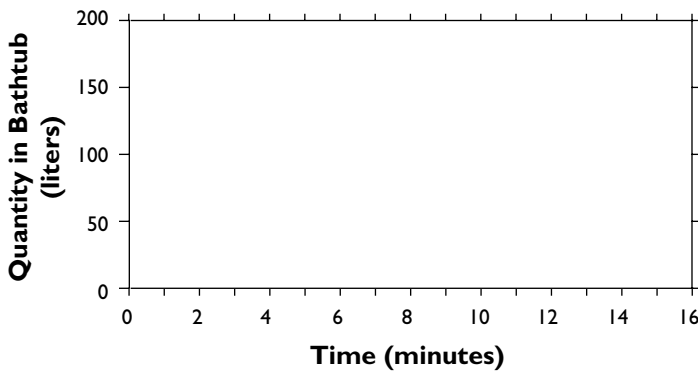
FIGURE 3. Understanding Stocks and Flows
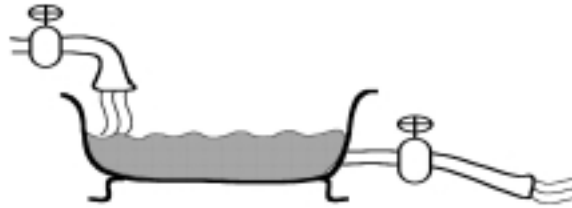
Consider the bathtub shown at left. Water flows in at a certain rate, and exits through the drain at another rate.
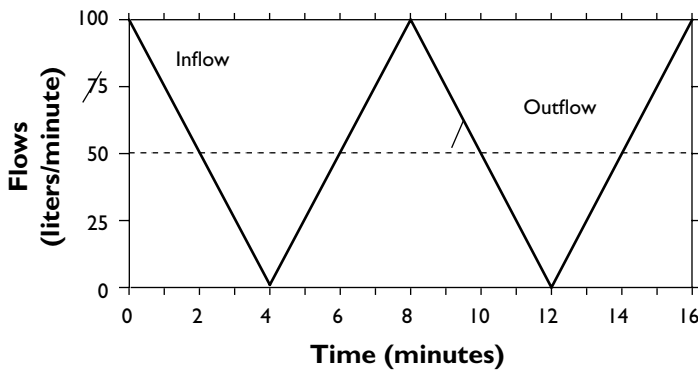
The graph at left shows the hypothetical behavior of the inflow and outflow rates for the bathtub. From that information, draw the behavior of the quantity of water in the tub on the second graph below.

Assume the initial quantity in the tub (at time zero) is 100 liters.

problems, many people drew trajectories that violated basic laws of physics such as conservation of matter.[9]

Attribution Errors and False Learning

Some people believe that experience and market forces enable good managers to learn quickly about the feedbacks and side effects of their decisions, including, as in the example above, the morale and workload impacts of layoffs or the low quality resulting from rushing a product to market. Unfortunately, few of us can say we've never faced such situations or been blindsided by

unanticipated side effects of our own actions. The heuristics we use to judge causal relationships systematically lead to cognitive maps that ignore feedbacks, nonlinearities, time delays, and other elements of dynamic complexity. To judge causality, we use cues such as temporal and spatial proximity of cause and effect, temporal precedence of causes, covariation, and similarity of cause and effect. In complex systems, however, cause and effect are often distant in time and space, and the delayed and distant consequences of our actions are different from and less salient than their proximate effects—or are simply unknown. The interconnectedness of complex systems causes many variables to be correlated with one another, confounding the task of judging cause. Research shows that few mental models incorporate any feedback loops. For example, studies have found virtually no feedback loops in the cognitive maps of political leaders; rather, the leaders focused on particular decisions they might make and their likely consequences—an event-level representation.[10] Experiments in causal attribution show people tend to assume each event has a single cause and often cease their search for explanations when the first sufficient cause is found.[11]

A fundamental principle of system dynamics states that the structure of the system gives rise to its behavior. In complex systems, different people placed in the same structure tend to behave in similar ways. However, people have a strong tendency to attribute the behavior of others to dispositional rather than situational factors—that is, to character (and, in particular, character flaws) rather than to the system in which these people are embedded. The tendency to blame other people instead of the system is so strong that psychologists call it the "fundamental attribution error."[12] In a famous study, psychologists Robert Rosenthal and Lenore Jacobson told a group of grade school teachers that test scores showed a particular 20% of their students would bloom academically in the year ahead. At the end of the year, those students showed larger increases in IQ than the others. There was only one problem: the apparently "gifted" students had been chosen entirely at random.[13] The teachers, without realizing it themselves, set higher expectations for the students labeled as gifted, gave them more help, provided more praise. Thus nurtured, these lucky students did bloom, though they were no different at the start than any of the other children in the class. The others necessarily received less attention, less help, and less praise, falling farther and farther behind. Without the ability to see how they themselves were part of the classroom and community system, how their own behavior helped some to excel while undermining others, the teachers interpreted events such as test grades and class participation as evidence confirming their preconceptions: The high performance of the students in the gifted group *proved* that they were truly gifted, and the poor performance of the rest *proved* that these were in fact the low achievers.

Because they were unaware of the ways in which the system structure shaped their behavior, the teachers learned a false lesson with pernicious consequences. The attribution of behavior to individuals and their character rather than system structure diverts our attention from the high leverage points where

redesign of the system can have significant, sustained, beneficial effects on performance. When we attribute behavior to people rather than system structure the focus of management becomes scapegoating and blame rather than the design of organizations in which ordinary people can achieve extraordinary results.

Tools of System Dynamics

To improve our ability to learn about and manage complex systems, we need tools capable of capturing the feedback processes, stocks and flows, time delays, and other sources of dynamic complexity. The tools must also enable us to understand how these structures create a system's dynamics and generate policy resistance. They must help us evaluate the consequences of new policies and new structures we might design. These tools include causal mapping and simulation modeling.

Much of the art of system dynamics modeling lies in discovering and representing the feedback processes and other elements of complexity that determine the dynamics of a system. One might imagine that there is an immense range of different feedback processes to be mastered before one can use system dynamics effectively. In fact, all dynamics arise from the interaction of just two types of feedback loops, positive (or self-reinforcing) and negative (or self-correcting) loops. Positive loops tend to reinforce or amplify whatever is happening in the system: The more nuclear weapons NATO deployed during the Cold War, the more the Soviet Union built, leading NATO to build still more. If a firm lowers its price to gain market share, its competitors may respond in kind, forcing the firm to lower its price still more. The larger the installed base of Microsoft software and Intel machines, the more attractive the Wintel architecture became as developers sought the largest market for their software and customers sought systems compatible with the most software; the more Wintel computers sold, the larger the installed base. These positive feedback loops are what chemists call *autocatalytic*—self-stimulating processes that generate their own growth, leading to arms races, price wars, and the phenomenal growth of Microsoft and Intel, respectively.

Negative loops counteract and oppose change. The less nicotine in a cigarette, the more smokers must consume to get the dose they need. The more attractive a neighborhood or city, the greater the migration from surrounding areas will be—increasing unemployment, housing prices, crowding in the schools, and traffic congestion until the city is no more attractive than other places people might live. The larger the market share of dominant firms, the more likely is government antitrust action to limit their monopoly power. These loops all describe processes that tend to be self-limiting, processes that create balance and equilibrium.[14]

As an illustration, suppose your firm is about to launch an innovative new product, one that creates an entirely new category with substantial market potential, but for which no market yet exists (e.g., personal computers in the

FIGURE 4. Building a Simulation Model

A. Causal Loop Diagram

B. Causal Diagram Showing Stock and Flow Structure
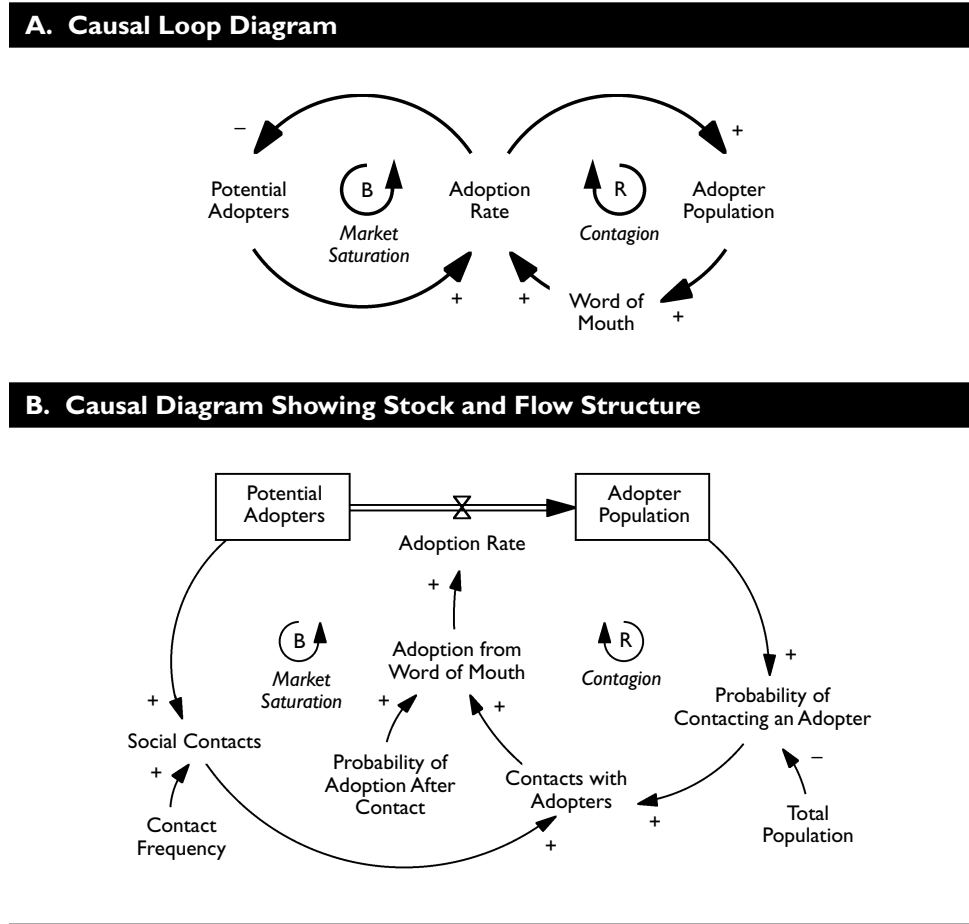
early 1980s). You need to understand how quickly and in what fashion the market might develop, how you can stimulate adoption, how the market will saturate, how to design the marketing mix and pricing strategy, and a host of other issues. You could begin by identifying some of the positive feedback processes that could stimulate adoption, and you could map them with a *causal loop diagram* (CLD).

Figure 4a shows two of the feedback processes you could identify. If the new product is sufficiently attractive, the early adopters will generate favorable word of mouth (WOM), stimulating further adoption, increasing the adopter population, and leading to still more WOM, in a positive feedback. The arrows in the diagram indicate the causal relationships. The positive (+) signs at the arrowheads indicate that the effect is positively related to the cause. Here, an increase in the adopter population causes the number of word of mouth encounters to rise above the number that would have occurred without the increase (and vice versa: a decrease in adopters causes the volume of WOM to fall below what it

FIGURE 4. Building a Simulation Model *(continued)*

C. Model Equations

Adoption Rate = Adoption from Word of Mouth [+ Adoption from Other Sources]

Adoption from Word of Mouth = Contacts with Adopters × Probability of Adoption After Contact

Contacts with Adopters = Social Contacts × Probability of Contacting an Adopter

Probability of Contacting an Adopter = Adopters ÷ Total Population

Social Contacts = Potential Adopters × Contact Frequency

D. Simulation
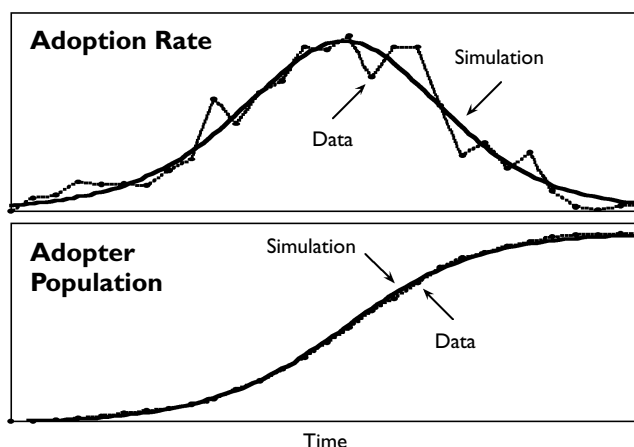
would have been). Similarly, more favorable WOM leads to a greater adoption rate, adding to the adopter population, and leading to still more WOM. The loop is self-reinforcing, hence the loop polarity identifier R. The loop is named the contagion loop to capture the process of social contagion by which the innovation spreads. If the contagion loop were the only one operating, the adoption rate and adopter population would both grow exponentially.

Of course, no real quantity can grow forever. There must be limits to growth. These limits are created by negative feedback. Negative loops are self-correcting. They counteract change. In the example, growing adoption of the innovation causes various negative loops to reduce adoption until use of the innovation comes into balance with its "carrying capacity" in the social and economic environment. As shown in Figure 4a, the adoption rate depends not only on word of mouth generated by adopters, but also on the number of potential adopters: The greater the number of potential adopters, the greater the probability that any adopter will come into contact with a potential adopter and, through word of mouth, cause that individual to adopt the innovation (hence the positive polarity on the link from Potential Adopters to the Adoption Rate).

However, the greater the adoption rate, the smaller the remaining population of Potential Adopters will be, limiting future adoption through market saturation (hence the negative (–) polarity for the link from the Adoption Rate to Potential Adopters). The B in the center of a loop denotes a balancing feedback.

The diagram shown here is deliberately simplified, showing only the most basic feedbacks. Your mapping process will likely identify a host of other loops, both reinforcing and balancing, that might be relevant in the diffusion process. These might include the learning curve (greater production experience lowers costs and price, increasing sales and experience still further) and scale economies (larger production volumes lead to efficiencies and greater purchasing power, allowing lower prices that lead to still more sales). Others might include positive network externalities arising from compatibility and the development of comple-mentary assets (e.g., the Wintel vs. Macintosh case). You could also identify negative feedbacks relating to, for example, entry of competitors, cannibalization of product sales as new generations of the product are introduced, and so on. Though not shown in the simple diagram in Figure 4, you could add each such loop to your diagram, creating a rich map of the feedbacks from which the prod-uct life cycle emerges.

Though there are only two types of feedback loop, complex systems can easily contain thousands of loops of both types, coupled to one another with multiple time delays, nonlinearities, and accumulations. The dynamics of all systems arise from the interactions of these networks of feedbacks. We can infer the dynamics of isolated loops such as those shown in Figure 4a. However, when multiple loops interact, it is generally impossible to determine what the dynamics will be by intuition. When intuition fails, we must turn to computer simulation.

To develop the simulation model, it is useful to augment the causal dia-gram to show the important stocks and flows explicitly, as shown in Figure 4b. The rectangles represent the stocks, in this case the populations of potential and actual adopters. The "pipe" connecting the two stocks represents the flow; in this case, adoption moves people from the potential adopter population into the adopter population. Figure 4b also shows how the word of mouth process works in more detail. Adoption resulting from word of mouth can be modeled as the product of the rate at which potential adopters have word of mouth encounters with adopters and the probability of adoption after such a contact. The more word of mouth encounters or the more persuasive each encounter, the greater the adoption rate. The rate at which potential adopters have word of mouth encounters depends on the total rate at which they have social contacts and the probability of contacting an adopter. That probability, in turn, depends on the proportion of adopters in the social networks to which the potential adopters belong. The total rate at which potential adopters contact others depends on the size of the potential adopter population and the frequency of social interactions in that group. Figure 4c shows the equations for this simple model.

Before simulating, you must estimate the parameters and initial conditions (e.g., the probability of adoption after contact with an adopter and the contact frequency). These parameters might be estimated using statistical means, market research data, analogous product histories, expert opinion, and any other relevant sources of data, quantitative or judgmental.

The overall dynamics of the system depend on which feedback loops are dominant. Figure 4d shows a simulation of the model compared to the data for the diffusion of a successful new computer. For a sufficiently attractive innovation, the self-reinforcing word of mouth loop dominates initially, and the adoption rate and adopter population grow exponentially. The growing rate of adoption, however, drains the stock of potential adopters, eventually constraining the adoption rate due to market saturation. The dominant feedback loop shifts from the positive contagion loop to the negative saturation loop. The shift in loop dominance is a fundamentally nonlinear process, which arises in this case because adoption requires a word of mouth encounter between an adopter and a potential adopter. The shift in loop dominance occurs at the point where the adoption rate peaks. The behavior of the system shifts from acceleration to deceleration, and the system gradually approaches equilibrium.

In this fashion, the modeling process can continue. The model should be augmented to include the other important loops identified through causal mapping. Simulation experiments may suggest new data to collect and new types of experiments to run to resolve uncertainties and improve the model structure. The model can also be used to design and evaluate new policies before implementing them in the real world. The results of these experiments in the real world can then lead to revisions and improvements in both the simulation model and the mental models of the decision makers, thus speeding the learning process.

Simulations are not tools to predict the future. Rather, they are virtual worlds or microworlds in which managers can develop decision-making skills, conduct experiments, and play.[15] Management flight simulators can be physical models, board games, or computer simulations. In systems with significant dynamic complexity, computer simulation will typically be needed.

Modern system dynamics modeling software makes it possible for anyone to participate in the modeling process. Graphical user interfaces enable modelers to quickly sketch a causal diagram, capturing the feedbacks, stocks and flows, time delays, and nonlinearities they identify. Equations can be written using so-called "friendly algebra" so that advanced mathematical training is no longer necessary (see Figure 4c). Modeling can now be done in real-time, and with groups. Simulation results can be viewed immediately. Sensitivity analysis, optimization, and calibration to data can be largely automated. A model can easily be converted into an interactive game with an intuitive interface. Of course, while the software has become easier and easier to use, modeling is not computer programming and remains a demanding activity. Better hardware and software do not replace the thinking process; rather, they provide a means to

improve our mental models and design more effective policies. They make it possible for everyone to participate in the modeling process and increase the time available to focus on the issues of concern.

Tools for learning about complexity must also facilitate the *process* of systems thinking and policy design. While the virtual world enables controlled experimentation, it does not require us to apply the principles of scientific method. Similarly, defensive routines and groupthink that thwart learning in teams can operate in the learning laboratory just as in the real organization. Effective modeling often requires members of the client team to recognize the limitations of their inquiry skills and address their own defensive behaviors. Managers unaccustomed to disciplined scientific reasoning and an open, trusting environment with learning as its goal will have to build these basic skills before a system dynamics model—or indeed, any model—can prove useful. Developing these skills takes effort and practice.[16]

The list of successful interventions using system dynamics is growing. Of course there are also failures, as the community of modelers continues to learn and improve the tools and process. Recent successful projects in the business world include strategy design for a highly successful wireless communications startup, leasing strategy for a large automaker, supply chain reengineering in a number of major high-technology firms, a new marketing strategy for a major credit card organization, long-range market forecasts and strategy development for a major commercial aircraft manufacturer, clinical trial and marketing strategies for new pharmaceuticals, models for effective management of large-scale projects in software, civil construction, shipbuilding, aerospace, defense, and commercial product development—and many others.

Applications

The articles that follow in this issue of the *California Management Review* apply system dynamics to some of the most difficult issues faced by organizations today. How can an organization escape the trap of firefighting, in which continual crisis fosters a short-term orientation that prevents investment in organizational capabilities that could prevent the crises? Why do so many process improvement programs fail? Why does product and service quality drift down despite an organization's efforts to maintain standards and satisfy their customers? Why don't people learn on their own how to avoid policy resistance and overcome these problems?

In "Past the Tipping Point: The Persistence of Firefighting in Product Development," Nelson Repenning, Paulo Gonçalves, and Laura Black develop a formal model of organizational firefighting. Their model shows how well-intentioned, hard-working engineers and managers can inadvertently slip into a trap in which low organizational capabilities are self-perpetuating. For example, in many firms new product development projects are routinely plagued by unexpected rework and low quality, forcing the team into last-minute heroics to hit

launch dates. These heroics, with their long hours and single-minded focus on getting the product out, prevent people from devoting effort to upstream work on the next-generation product, which then reaches the launch stage even farther behind, triggering a new round of crises and the need for still more heroic firefighting. They show that many policies undertaken to escape the trap—including many programs to implement new product development processes and tools—are self-defeating, and they explore effective policies to overcome the trap.

Nearly every firm in the U.S. has made quality and customer satisfaction a centerpiece of their mission and values, spending billions on quality programs in the process, yet the American Customer Satisfaction Index is stagnant at about 80% for manufacturing and only 70% for services, down nearly 7% since 1995. In "Tradeoffs in Responses to Work Pressure in the Service Industry," Rogelio Oliva examines this paradox. Obviously service quality can fall if the demand for service outstrips an organization's resources. Oliva shows that quality can erode steadily even when demand and resources are, on average, sufficient. Random variations in workload lead to temporary periods of high workload that often cause service workers to cut corners and spend less time with customers in an attempt to meet throughput and cost targets. These shortcuts gradually become embedded in norms for customer interaction. Since service quality is intrinsically subjective and less salient than cost and throughput metrics, management often interprets the reduction in the time spent with each customer as a productivity gain, justifying a reduction in service resources. Workload during peak times increases still further, forcing employees to cut corners still more. Oliva shows how these dynamics played out in a major commercial bank, leading to steady quality erosion and reduced revenue.

Why don't people, particularly senior managers, learn to recognize and avoid these traps through experience? Why do firefighting, quality erosion, and short-term thinking persist? Part of the answer lies in the way our mental models lead us to interpret the data we receive from complex systems. As in the example of the teachers discussed above, we tend to assume cause and effect are closely related in time and space, attributing events such as low test scores, late product launches, or customer complaints to the intrinsically low IQ, undisciplined work habits, or poor attitude of the students, engineers, or customer service representatives, rather than to the pressures created by the system in which they are embedded. In "Nobody Ever Gets Credit for Fixing Problems that Never Happened: Creating and Sustaining Process Improvement," Nelson Repenning and I show how managers in a large automaker erroneously attributed their difficulties to the poor attitudes and work habits of employees. Though these attributions were wrong, the feedback managers received from the system caused their false beliefs to be strongly self-fulfilling, crippling their efforts to improve the product development process. Worse, some managers involved in the failed effort came away with stronger prejudices and stereotypes about the low skills and poor attitudes of the employees, further intensifying cynicism and

eroding trust in the organization, thus making genuine improvement even less likely. The article closes with case examples of organizations that have successfully used system dynamics and management flight simulators to overcome these dynamics and achieve dramatic results. These successes show that what often prevents us from overcoming policy resistance and achieving high performance is not a lack of resources, technical knowledge, or a genuine commitment to change. What thwarts us is our lack of a meaningful systems-thinking capability, the capability to learn about complexity and find the high leverage policies through which we can create the future we truly desire.

Notes

1. Lewis Thomas, *The Medusa and the Snail: More Notes of a Biology Watcher* (New York, NY: Viking Press, 1979), p. 90.
2. There are many schools of systems thinking. For a survey, see George Richardson, *Feedback Thought in Social Science and Systems Theory* (Philadelphia, PA: University of Pennsylvania Press, 1991). See also Peter Senge, *The Fifth Discipline: The Art and Practice of the Learning Organization* (New York, NY: Doubleday, 1991). Some emphasize qualitative methods, others stress formal modeling. For sources of method and metaphor, they draw on fields as diverse as anthropology, biology, engineering, linguistics, psychology, physics, and Taoism, and seek applications in fields still more diverse. All agree, however, that a systems view of the world is still rare. Jay Forrester developed system dynamics in the 1950s at MIT.
3. See John Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World* (New York, NY: Irwin/McGraw-Hill, 2000), <www.mhhe.com/sterman>. Includes extensive references to the literature and a disc containing over 60 simulation models.
4. See the late Herbert Simon's concept of bounded rationality. Herbert Simon, *Sciences of the Artificial*, 3rd ed. (Cambridge, MA: The MIT Press, 1996).
5. For descriptions of the Beer Game, see Sterman, op. cit. and Senge, op. cit.
6. See Sterman, op. cit., chapter 17, for discussion and examples.
7. See Art Schneiderman, "Setting Quality Goals," *Quality Progress*, 21/4 (April 1988): 55-57. Sterman et al. show how these differential improvement rates led to difficulty at a leading semiconductor manufacturer. J. Sterman, N. Repenning, and F. Kofman, "Unanticipated Side Effects of Successful Quality Programs: Exploring a Paradox of Organizational Improvement," *Management Science*, 43/4 (1997): 501-521.
8. See I. Dierickx and K. Cool, "Asset Stock Accumulation and Sustainability of Competitive Advantage," *Management Science*, 35/12 (December 1989): 1504-1511. Intangibles have long been included in system dynamics models. See, for example, Jay Forrester, *Collected Papers of Jay W. Forrester* (Waltham, MA: Pegasus Communications, 1975). System dynamics modeling stresses the importance of and methods to operationalize and quantify such so-called soft variables (variables for which no numerical data may be available). Omitting such concepts assumes their impact is zero, one of the few assumptions we know to be wrong.
9. For the solution, discussion, and other examples, see Linda Booth Sweeney and John Sterman "Bathtub Dynamics: Initial Results of a Systems Thinking Inventory," *System Dynamics Review*, 16/4 (2000): 249-294.
10. See Robert Axelrod, *The Structure of Decision: The Cognitive Maps of Political Elites* (Princeton, NJ: Princeton University Press, 1976); Dietrich Dörner, *The Logic of Failure* (New York, NY: Henry Holt, 1996).

11. See Scott Plous, *The Psychology of Judgment and Decision Making* (New York, NY: McGraw Hill, 1993).

12. See Plous, op. cit.; L. Ross, "The Intuitive Psychologist and His Shortcomings: Distortions in the Attribution Process," in L. Berkowitz, ed., *Advances in Experimental Social Psychology*, Volume 10 (New York, NY: Academic Press, 1977).

13. See R. Rosenthal and L. Jacobson, *Pygmalion in the Classroom*, expanded edition (New York, NY: Irvington, 1992).

14. Negative loops do not always result in a smooth and stable adjustment to equilibrium. Time delays can cause overshoot and oscillation as corrective actions persist too long. Such delays are pervasive and so too are fluctuations, from the fluctuations in your blood sugar level (caused by delays in the synthesis of insulin) to boom and bust cycles in real estate, semiconductors, shipbuilding, and other industries (caused by delays in adjusting production and production capacity to changes in demand and prices). See Sterman, op. cit.

15. The term virtual world is due to Donald Schön, *The Reflective Practitioner* (New York, NY: Basic Books. 1983). Papert discusses microworlds in Seymour Papert, *Mindstorms* (New York, NY: Basic Books, 1980).

16. See John Morecroft and John Sterman, eds., *Modeling for Learning Organizations* (Portland, OR: Productivity Press, 1994); P. Senge et al., *The Dance of Change: The Challenges to Sustaining Momentum in Learning Organizations* (New York, NY: Doubleday, 1999).