

System Dynamics Modeling for Public Health: Background and Opportunities

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The systems modeling methodology of system dynamics is well suited to address the dynamic complexity that characterizes many public health issues. The system dynamics approach involves the development of computer simulation models that portray processes of accumulation and feedback and that may be tested systematically to find effective policies for overcoming policy resistance.

System dynamics modeling of chronic disease prevention should seek to incorporate all the basic elements of a modern ecological approach, including disease outcomes, health and risk behaviors, environmental factors, and health-related resources and delivery systems. System dynamics shows promise as a means of modeling multiple interacting diseases and risks, the interaction of delivery systems and diseased populations, and matters of national and state policy. (*Am J Public Health*. 2006;96:452–458. doi:10.2105/AJPH.2005.062059)

By applying a remedy to one sore, you will provoke another; and that which removes the one ill symptom produces others, whereas the strengthening one part of the body weakens the rest.

—Sir Thomas More, *Utopia*, Part I (1516)

DESPITE REMARKABLE

successes in some areas, the health enterprise in America still faces difficult challenges in meeting its primary objective of reducing the burden of disease and injury. Examples include the growth of the underinsured population, epidemics of obesity and asthma, the rise of drug-resistant infectious diseases, ineffective management of chronic illness,¹ long-standing racial and ethnic health disparities,² and an overall decline in the health-related quality of life.³ Many of these complex problems have persisted for decades, often proving resistant to attempts to solve them.⁴

It has been argued that many public health interventions fall short of their goals because they are made in piecemeal fashion, rather than comprehensively and from a whole-system perspective.⁵ This compartmentalized approach is engrained in the financial structures, intervention designs, and evaluation methods of most health agencies. Conventional analytic methods are generally unable to satisfactorily address situations in which population needs change over time (often in response to the interventions themselves), and in which risk factors, diseases,

and health resources are in a continuous state of interaction and flux.⁶

The term *dynamic complexity* has been used to describe such evolving situations.⁷ Dynamically complex problems are often characterized by long delays between causes and effects, and by multiple goals and interests that may in some ways conflict with one another. In such situations, it is difficult to know how, where, and when to intervene, because most interventions will have unintended consequences and will tend to be resisted or undermined by opposing interests or as a result of limited resources or capacities.

THE SYSTEM DYNAMICS APPROACH

We believe that in many cases the challenges of dynamic complexity in public health may be effectively addressed with the systems modeling methodology of system dynamics. The methodology involves development of causal diagrams and policy-oriented computer simulation models that are unique to each problem setting. The approach was developed by computer pioneer Jay W. Forrester in the mid-1950s and first described at length in his book *Industrial Dynamics*,⁸ with some additional principles presented in later works.^{9–12} The International System Dynamics Society was established in 1983, and within the society a special

interest group on health issues was organized in 2003.

A central tenet of system dynamics is that the complex behaviors of organizational and social systems are the result of ongoing accumulations—of people, material or financial assets, information, or even biological or psychological states—and both balancing and reinforcing feedback mechanisms. The concepts of accumulation and feedback have been discussed in various forms for centuries.¹³ System dynamics uniquely offers the practical application of these concepts in the form of computerized models in which alternative policies and scenarios can be tested in a systematic way that answers both “what if” and “why.”^{14–16}

A system dynamics model consists of an interlocking set of differential and algebraic equations developed from a broad spectrum of relevant measured and experiential data. A completed model may contain scores or hundreds of such equations along with the appropriate numerical inputs. Modeling is an iterative process of scope selection, hypothesis generation, causal diagramming, quantification, reliability testing, and policy analysis.⁷ The refinement process continues until the model is able to satisfy requirements concerning its realism, robustness, flexibility, clarity, ability to reproduce historical patterns, and ability to generate useful insights. These numerous requirements help to ensure that a model is reliable and useful not only for studying

the past, but also for exploring possible futures.^{12,17}

The calibration of a system dynamics model's numerical inputs—its initial values, constants, and functional relations—merits special mention. In system dynamics modeling, variables are not automatically excluded from consideration if recorded measurements on them are lacking. Most things in the world are not measured, including many that experience tells us are important. When subject matter experts agree that a factor may be important, it is included in the model, and then the best effort is made to quantify it, whether through (in approximately this order of preference) the use of recorded measurements, inference from related data, logic, educated guesswork, or adjustments needed to provide a better simulated fit to history.^{11,17,18} Uncertainties abound in model calibration, which is one of the reasons that sensitivity testing is critical. Sensitivity testing of a well-built system dynamics model typically reveals that its policy implications are unaffected by changes to most calibration uncertainties.^{9,10} But even when some uncertainties are found to affect policy findings, modeling contributes by identifying the few key areas—out of the overwhelming number of possibilities—in which policymakers should focus their limited resources for metrics creation and measurement.

System dynamics modeling has been applied to issues of population health since the 1970s. Topic areas have included the following:

1. Disease epidemiology including work in heart disease,^{19–21}

- diabetes,^{21,22} HIV/AIDS,^{23–25} cervical cancer,²⁶ chlamydia infection,²⁶ dengue fever,²⁷ and drug-resistant pneumococcal infections²⁸;
2. Substance abuse epidemiology covering heroin addiction,²⁹ cocaine prevalence,³⁰ and tobacco reduction policy^{31,32};
3. Patient flows in emergency and extended care^{26,33–35};
4. Health care capacity and delivery in such areas as population-based health maintenance organization planning,³⁶ dental care,^{37,38} and mental health,³⁸ and as affected by natural disasters or terrorist acts³⁹;
5. Interactions between health care or public health capacity and disease epidemiology.^{40–43}

Most of these modeling efforts have been done with the close involvement of clinicians and policymakers who have a direct stake in the problem being modeled. A good example is a chronic illness study conducted in Whatcom County, Washington, that focused on diabetes and heart failure.²¹ Health care providers, payers, and community representatives (supplemented by the health care literature) identified influential variables, articulated policy-related concerns, provided data, and provided experience-based estimates when measured data were not available. The models projected the potential impacts of programs on morbidity, mortality, disability, costs, and the various stakeholders and identified the programmatic investments required. Established system dynamics techniques for group model building⁴⁴ can help to harness the insights and involvement of those who deal with public health problems on a day-to-day basis.

It is useful to consider how system dynamics methodology and models compare with those of other simulation methods that have been applied to public health issues, particularly in epidemiological modeling. Other types of models include lumped population contagion models^{45,46}; Markov models that distinguish among demographic categories of age, sex, race, and so forth^{47–49}; and microsimulations or agent-based models at the level of individuals.^{50–52} There is significant overlap among the methods, and one cannot always look at a model's equations and instantly know by what method it was developed. In general, though, one may say that system dynamics models tend to have broader boundaries than other types of models and accordingly tend to admit more variables on the basis of logic or expert opinion and for which solid statistical estimates may not be available. System dynamics modelers find that a broad boundary including a variety of realistic causal factors, policy levers, and feedback loops is often what is needed for finding effective solutions to persistent, dynamically complex problems.^{7,53}

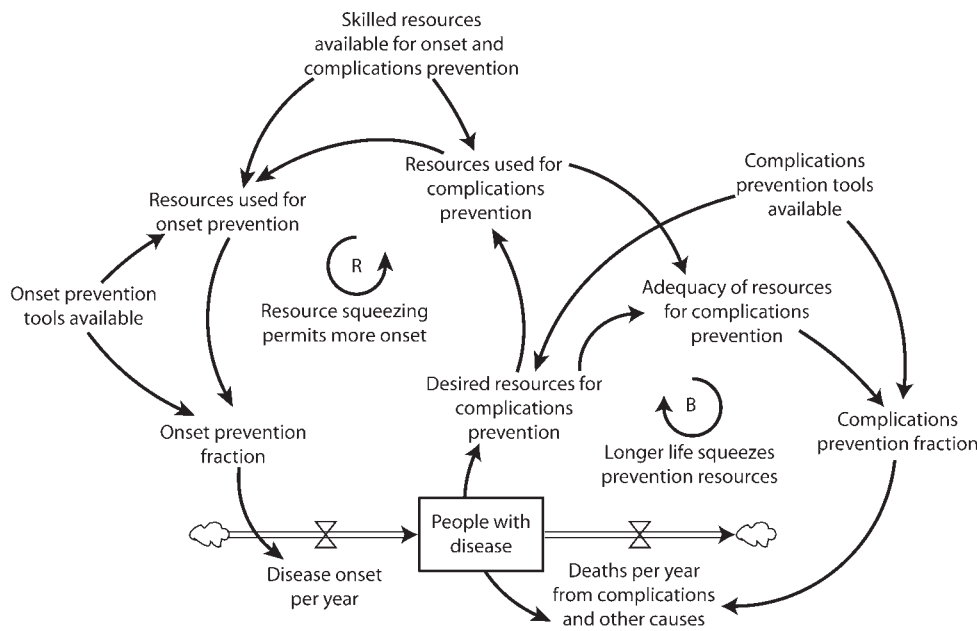
CHRONIC DISEASE PREVENTION

The value of system dynamics modeling is best explained by way of illustration. We start with a challenging question: Why is it that, despite repeated calls for a greater emphasis on primary prevention of chronic disease (including a prominent recent example⁵⁴), the vast majority of health activities and expenditures in the United States are made not for such prevention but rather for disease management and care?⁵⁵ This dominance of

“downstream” over “upstream” health activities appears to have grown ever greater during the era of modern medicine and is now seen as a pressing problem by public health agencies such as the Centers for Disease Control and Prevention (CDC).⁵⁶

To illustrate how system dynamics simulation might shed light on this question, we have built a relatively simple model exploring how a hypothetical chronic disease population may be affected by 2 types of prevention: upstream prevention of disease onset, and downstream prevention of disease complications. The model demonstrates how upstream prevention may become inadvertently “squeezed out” by downstream prevention and suggests that a focusing of resources on life-extending clinical tools may ultimately hurt more than it helps. The model has only a single aggregated population stock, 27 differential and algebraic equations and 12 numerical inputs, and is based on general knowledge rather than on any specific case study or other hard data. If the model were intended for actual policy-making and not only for illustration or exploration, one would certainly expect to see a more detailed depiction of the population and causal factors and policies, and a more data-reliant approach to parameter estimation.

Figure 1 presents the model's essential causal structure and policy inputs. The single stock of people with disease represents the gradually changing net accumulation of 2 flows: an inflow of disease onset and an outflow of deaths. Skilled resources for prevention, consisting perhaps of all primary care providers in the region where the disease population is located, are assumed to be



Note. The rectangle represents a stock of people; thick arrows with valves and cloud symbols represent flows of people; thinner arrows indicate causal influence; arrows with minus signs indicate inverse causal influence.

FIGURE 1—A simple model of chronic disease prevention.

on patients. Our starting assumptions are that 25% of complications are preventable, 25% of onset is preventable, and resources are sufficient to achieve both these prevention fractions, with some capacity to spare. Under these assumptions, upstream prevention activities are significant and nearly on a par with downstream prevention activities. This balanced situation may be similar to the state of affairs that prevailed in general medicine several decades ago when the tools of disease diagnosis and management were limited—and very unlike the situation today.

Figure 2 presents simulation output, over a period of 50 years, for 4 key variables (onset prevention fraction, complications prevention fraction, people with disease, and deaths from

fixed in number. Certain clinical tools (diagnostic and therapeutic) are available to these providers for complications prevention, and other tools are available for onset prevention. The greater the number of people with disease, and the greater the number of tools available for complications prevention, the more the time of providers will be devoted to complications prevention. The remainder of provider time is then available for onset prevention efforts among nondiseased patients (to the extent that available onset prevention tools allow) or is absorbed by other, nonprevention activities.

For both types of prevention, assumptions are made about the preventable fractions of cases given existing clinical tools, and also about the resource requirements per case prevented, and the time delay between the availability of new tools and their adoption by providers and impact

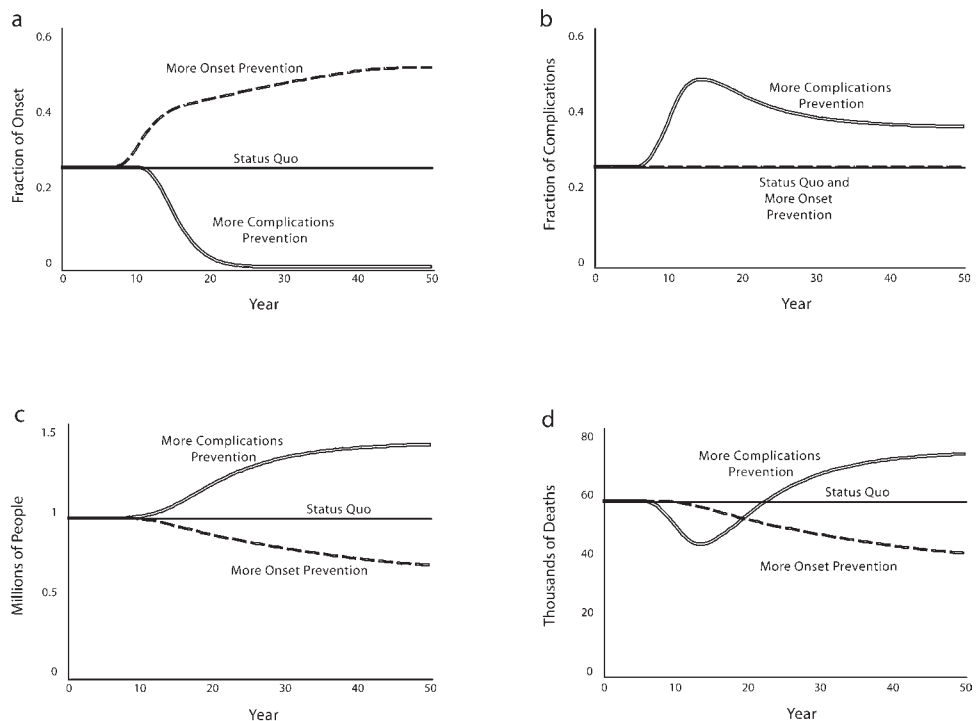


FIGURE 2—Chronic disease prevention model output for 3 scenarios over 50 simulated years, showing onset prevention fraction (a), complications prevention fraction (b), people with disease (c), and deaths from complications (d).

complications) under 3 different policy scenarios we have tested (Status Quo, More Complications Prevention, and More Onset Prevention). In all 3 scenarios, the model has been initialized in a dynamic equilibrium or steady state in which there are about 1 million people with disease, with 75 000 new cases per year and an equal number of deaths, and with 56 000 of the annual deaths from complications. In the Status Quo scenario, no new prevention tools are introduced during the simulation; consequently, the graph lines remain flat, making this scenario a convenient baseline for comparison.

In the More Complications Prevention scenario, new tools for complications prevention become available during years 5 to 10, increasing the preventable fraction of complications from 25% to 50%. The results look good early on, as a rising complications prevention fraction (Figure 2b) leads to a significant reduction in complications deaths (Figure 2d). But the reduction in deaths means a longer average stay in the diseased population stock and thus, an increase in the number of people with disease (Figure 2c). Greater disease prevalence, in turn, increases the need for resources for complications prevention.

This increased demand for limited resources has 2 negative effects. The first is that resources become inadequate to prevent complications in some patients who could have been helped otherwise. Consequently, the complications prevention fraction starts to fall from its peak, and the number of deaths starts to rebound. This effect, reflecting the balancing (B) loop seen in the right-hand portion of Figure 1, is unfortunate but by itself would

cause only a limited rebound in deaths. More problematic is the second effect of resource squeezing, which is a decline in the onset prevention fraction (Figure 2a). The drop in onset prevention allows a further increase in disease prevalence, which causes more resources to be absorbed in complications prevention, leaving even less for onset prevention. This reinforcing (R) loop, seen in the left-hand portion of Figure 1, ultimately drives out onset prevention entirely, leading to large permanent increases in both disease prevalence and complications deaths relative to their starting points.

To summarize this second scenario, although the complications prevention fraction is in fact permanently increased, the prolongation of life and the squeezing out of onset prevention ultimately cause the prevalence of disease to increase proportionately even more; the net result is an increase in deaths from complications. The squeezing out of onset prevention is a vicious cycle and a trap that the health care system may be prone to fall into, given its commitment to the best possible management of existing disease. In a system with limited prevention resources, this well-intentioned commitment may end up doing more harm than good. (The over-dependence on downstream work and squeezing out of upstream work has been observed in many domains outside of health care. This archetypical “fire fighting” dynamic has been the subject of SD models in the area of product development⁵⁷ and business process improvement.⁵⁸)

A much brighter outcome is seen in the third scenario in Figure 2, More Onset Prevention. In this scenario, new tools for onset

prevention become available during years 5 to 10, increasing the preventable fraction of onset from 25% to 50%. Using the spare resources initially available, some additional onset is prevented (Figure 2a), and the number of people with disease (Figure 2c) declines. As disease prevalence declines, even more prevention resources are freed up to do onset prevention. With disease prevalence decreasing in this scenario, the reinforcing loop in Figure 1 becomes a “virtuous cycle” rather than a vicious cycle, making possible a long-term decline in both disease prevalence and deaths from complications (Figure 2d). A similar beneficial result might be obtained by other means; for example, by changes in funding mechanisms that shift more resources toward onset prevention.

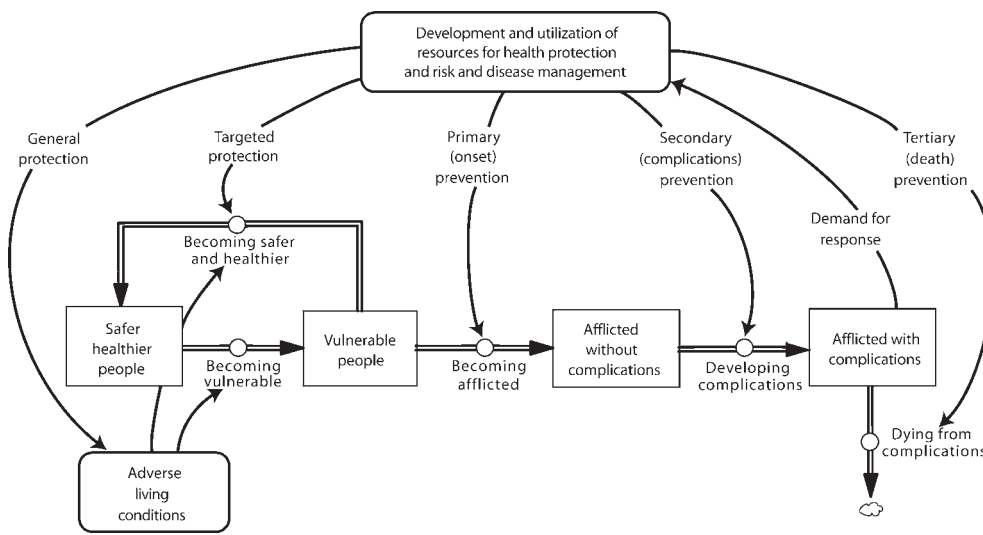
TOWARD MORE COMPLETE MODELS OF POPULATION HEALTH

The preceding example, exploring the interplay of a diseased population and the utilization of health resources, gives some indication of how a broader view of health dynamics can yield insights that would be out of the grasp of a less integrated approach. But system dynamics modeling can and should go further still to incorporate all the basic elements of a modern ecological approach that can help public health agencies achieve their goals of disease prevention, health promotion, and assurance of healthy conditions. Such a broad approach would encompass disease, health and risk behaviors, environmental factors, and resources that provide health and social services or are involved in health-related social transformation.^{59,60} Figure 3

presents a system dynamics–type diagram for thinking about the dynamics of population health in these broader terms. This framework has been used at the CDC in discussions about how the agency should move forward in an era of expanded public health goals and greater health challenges.⁵⁶

Only a few system dynamics studies to date have gone beyond diagramming to explore by means of simulation a more complete view of health like that seen in Figure 3. One such study is described by Homer and Milstein.⁴³ Their community health model examines the typical feedback interactions among broadly defined states of affliction prevalence, adverse living conditions, and the community’s capacity to act. Like the chronic disease prevention model presented earlier, the community health model is relatively compact and was not developed on the basis of any specific case. Nonetheless, sensitivity testing of the model across many possible community and affliction characteristics has led to some conclusions about how different types of outside assistance are likely to affect a community in the short and long term. For example, the model suggests that outside assistance focused on building a community’s capacity to act may be the most effective place to start in a community struggling against disease and poverty, ensuring longer-term success in a way that more direct interventions fail to do.

Hirsch and Immediato^{40,61} describe another more complete view of health. Their Health Care Microworld, depicted in highly simplified form in Figure 4, simulates the health status of and health care delivered to a population. The Microworld was created



Note. Rectangles represent the stocks of people; thick arrows with circles represent flows of people; thinner arrows indicate causal influence; rounded rectangles indicate multidimensional concepts.

FIGURE 3—A broad view of population health and the spectrum of possible responses.

realistic picture of their overall epidemiology and policy implications, particularly where the diseases and risks are mutually reinforcing. For example, it has been found that substance abuse, violence, and AIDS often cluster in the same urban subpopulations, and that such “syndemics” are resistant to narrow policy interventions.^{62–64} This idea could also be extended to the case of mental depression, which is often exacerbated by other chronic illnesses and may, in turn, interfere with the proper management of those illnesses. An exploratory simulation model has indicated that system dynamics can usefully address the concept of syndemics.⁶⁵

There is also more to be learned about health-related delivery systems and capacities, with the inclusion of characteristics specific to selected real-world cases. Models combining delivery systems and risk and disease epidemiology could help policymakers and health care providers understand the nature of coordination required to put ambitious public health and risk reduction programs in place without overwhelming delivery capacities. Such models could reach beyond the health care delivery system per se to examine the potential roles of other delivery systems, such as schools and social service agencies, in health risk reduction.

The more complete view of population health dynamics advocated here may also be extended to address persistent challenges that will likely require policy changes at a national and state level, and not only at the level of local communities. Examples include the large underinsured population, high health care costs, and the shortage of nurses. System dynamics modeling can help to identify the feedback loops

for a consortium of health care providers who were facing a wide range of changes in the mid-1990s and needed a means for their staff to understand the implications of those changes for how they managed. The underlying system dynamics model is quite large and was designed to reflect with realistic detail a typical American community and its providers, with data taken from public sources as well as proprietary surveys. Users of the Microworld have a wide array of options for expanding the capacity and performance of the community’s health care delivery system such as adding personnel and facilities, investing in clinical information systems, and process redesign. They have a similar range of alternatives for improving health status and changing the demand for care, including screening for and enhanced maintenance care of people with chronic illnesses, programs to reduce behavioral risks such as smoking and alcohol abuse, environmental protection,

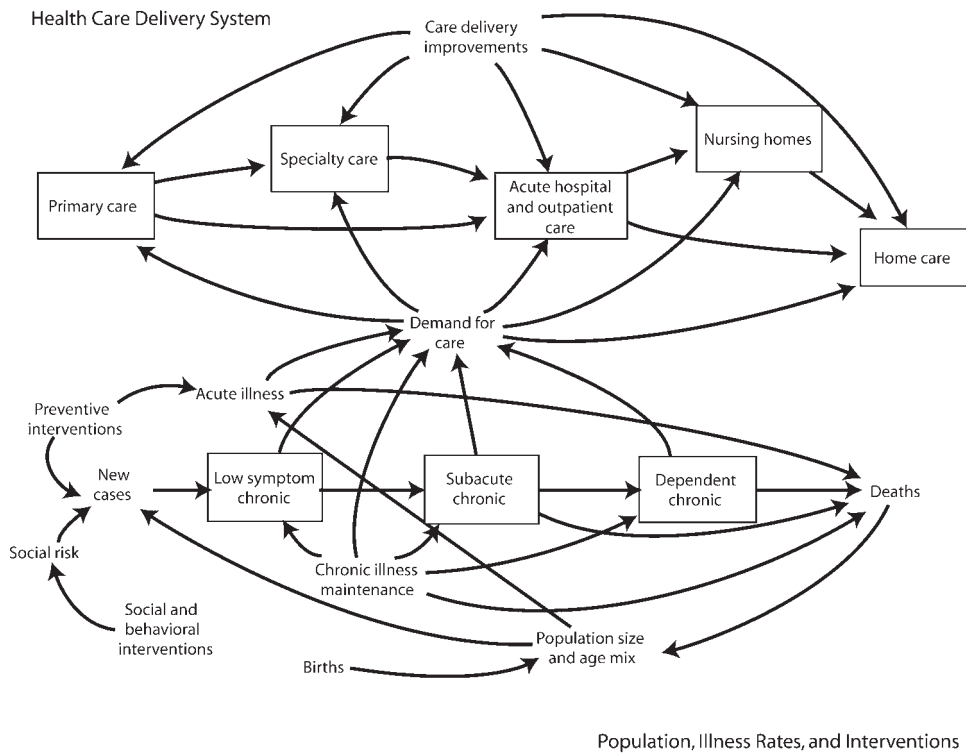
and longer-term risk reduction strategies such as providing social services, remedial education, and job training.

The Microworld’s comprehensive view of health status and health care delivery can provide insights not available from approaches that focus on 1 component of the system at a time. For example, users can play roles of different providers in the community and see how attempts at creating integrated delivery systems tend to fail when participating providers care more about their own bottom lines and prerogatives than about creating a viable system. When examining strategies for improving health status, users can get a better sense of how a focus on enhanced care of people with chronic illnesses provides short-term benefits in terms of reduced deaths, hospital admissions, and costs, but how better long-term results can be obtained by also investing in programs that reduce social and behavioral health risks. When

health care delivery and health improvement are combined, users can appreciate the pitfalls of launching ambitious health improvement programs before first expanding the capacity of the delivery system to provide the medical aspects of those programs.

OPPORTUNITIES AND NEW DIRECTIONS

As long as there are dynamically complex health issues in search of answers, the system dynamics approach will have a place in the analytic armamentarium. It has already made significant contributions to addressing epidemiological issues, as well as issues of health care capacity and delivery and patient flow management. There is still much to be learned about the population dynamics of individual chronic conditions like hypertension and risk factors like obesity. system dynamics models could also address multiple interacting diseases and risks, giving a more



Source. Adapted from Hirsch and Immediato.⁶¹
 Note. Episodes of illness in the bottom half of the diagram determine demand for care in the top half of the diagram. Rectangles in the bottom half represent stocks of ill patients. Rectangles in the top half represent stocks of provider capacity and workload. Arrows represent causal influences.

FIGURE 4—Overview of the health care microworld.

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responsible for these problems and point the way to policies that can make a lasting difference. ■

About the Authors

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