Problems for the Future of System Dynamics

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The field of system dynamics first envisioned by Forrester in 1956 is approaching its fortieth anniversary. It has experienced two significant revolutions: changes in practice wrought by the development of iconographic software[1] and the shift from modeling to improve a process to modeling for the purpose of improving people's mental models (Forrester 1992). Its third revolution — expanding the pool of practicing modelers far beyond the nucleus who have received university training — has been underway since STELLA hit the schools in the late 1980s. A fourth revolution — moving to the forefront qualitative modeling based on word-and-arrow archetypes — began quietly in the mid 1980s (e.g., Wolstenholme and Coyle 1983) and exploded on the scene with the publication of *The Fifth Discipline* (Senge 1990). These recent and ongoing revolutions carry promise and potential pitfalls for the field.

The potential pitfalls of our current successes suggest the time is right to sketch a view of outstanding problems in the field of system dynamics, to focus the attention of people in the field on especially promising or especially problematic issues. The list that follows should be thought of as the opening remarks in what I hope becomes an increasingly interesting conversation among practitioners. It stems from reflections on practice in the field during my tenure as editor of the *System Dynamics Review,* but other than the view from that mountaintop I can claim no particular expertise for the task. It seems vital for the field, however, that we begin the conversation, and so I offer the following initial statement of Problems for the Future of System Dynamics.

There is a double meaning here, which is intended: the problems we list should be deep and difficult problems worthy of attention now and in the future, and they should be of such magnitude that if not addressed they will pose problems for the field's future. In two senses, then, we are discussing Problems for the Future of the Field.

The initial list contains eight problem areas:

- Understanding model behavior
- Accumulating wise practice
- Advancing practice
- Accumulating results
- Making models accessible
- Qualtative mapping and formal modeling
- Widening the base
- Confidence and validation

The goal of the list is to initiate discussion of an agenda for concerted work in the field of system dynamics. If indeed these are the deep, difficult, and important problems facing the field, then we should begin to address them in collaborative and productively competitive ways.

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1 STELLA (High Performance Systems), and later Vensim (Ventana Systems) and PowerSim (ModelData).

Understanding model behavior.
The principal outstanding technical problem in simulation modeling is the development of tools to aid understanding model behavior.

For more than thirty five years practitioners have relied on a time-consuming and often incomplete process that iterates from formulation to parametrization, testing, observation, hypothesizing and back again. (See, for example, Richardson and Pugh 1981, 267-276.) Understanding connections between complex model structure and behavior comes, if one is skillful and/or lucky, after a prolonged series of model tests of deepening sophistication and insight.

Alternatively, and undoubtedly preferably, understanding connections between model structure and behavior comes from a sequential modeling process that moves from simpler formulations to more complex structure. [Richmond has urged, for example, that the modeler first build a complete, simulated model that is understandably simple, and then move from that toward complexity; he argues that attempts to build a complex model at the outset are likely to be doomed to failure.] At each stage, understandings from the previous simpler stage guide the path to understandings of the current structure. The process at each stage is still the time-consuming iteration of tests, observations, and hypotheses, but it is undoubtedly speeded by understandings codified at the previous stages of model complexity.

Technical support for understanding the connections between model structure and behavior is weak to the point of being almost nonexistent. In most of the software in use in system dynamics, there is no such support. The most sophisticated tools we have at hand in software are the causal tracing tools and graphs in Vensim.[2] Using these tools one can quickly move backward or forward in causal chains in a model to track down the source of intriguing behavior in a particular variable. While causal tracing capabilities are a major step forward in simulation-based tools available to us, they are still inadequate to the task of understanding the behavior of complex models. We are still forced to operate as we have for almost forty years, in a time-consuming and only gradually illuminating iterative process of hypotheses and tests.

There are some potentially promising directions. The dissertations of Nathan Forrester (1982) and Robert Eberlein (1984) contain approaches to understanding model behavior that rest, respectively, on eigenvalue elasticities and participation factors (see Richardson 1986 for a summary). In those works, formal analyses based on eigenvalues were used to identify dominant structure and, in Eberlein's work, to reduce a complex model to a simpler structure while preserving particular behavior modes of interest. In a sense, *simplifying a complex structure while preserving a behavior of interest* is one way of saying what we mean by *understanding the connections between structure and behavior*. However, both of these approaches rest on mathematics appropriate for linear systems and their applicability to nonlinear systems has not been tested in our literature beyond the work of these authors.[3]

Richardson (1984/1995) contains a simpler approach that directly addresses nonlinearity and the shifts in loop dominance that nonlinearities can cause. Mojtahedzadeh (1995) is pursuing a generalization of this approach that appears to be a promising step forward and in the process is

[2] Ventana Systems, 149 Waverley Street, Belmont, MA 02178.

[3] It is undoubtedly significant that Eberlein has not embedded eigenvalue-based model analysis tools in Vensim.

striving to clarify what we mean by understanding. But clearly more effort is in order. If wider audiences are to build and understand models to aid their own thinking or the thinking of others, then our software must do more than provide model diagrams to help with the building. Of the three tasks — model conceptualization, model formulation, and model understanding — unquestionably the two most difficult are the two that are least formal — conceptualization and understanding. The future of the field needs software support for understanding the links between stock-and-flow/feedback structure and dynamic behavior.

Accumulating wise practice

The field of system dynamics needs improved mechanisms for accumulating and promulgating insights about wise modeling practice.

In forty years of research and applications, system dynamics practitioners have solved many practical modeling problems. Wise practice includes insightful statements about

- building blocks of system structure: stock-and-flow structures, and elementary generic processes
- molecules of generically useful model structure — more complex than building blocks
- consulting wisdom
- group modeling principles
- teaching practice that accelerates growth in modeling capabilities
- wisdom about problem definition and system conceptualization
- wisdom about building confidence in models for policy analysis

Yet it is hard to locate the wisest statements about modeling practice. Searchers would begin, of course, with Forrester's classics (1961, 1968, 1969, 1971) and with the award-winning books and articles in the field.[4] But one should not miss the lesser known classics, such as Meadows (1982), Ford and Gardiner (1979), Homer (1983), and others

In addition to the great works in the field, embedded throughout our literature are

- solutions to modeling puzzles, such as the formulation and initialization of a coflow for years of experience of a work force; a robust formulation for the fraction of a resource like petroleum that can flow from a level like proven reserves; formulations for energy retrofits, managerial recruitment, training, and attrition; continuous (aggregate) logic; statistical measures in continuous models; and so on.
- wisdom about model-based consulting practice from the decades of experience of the great system dynamics consulting firms
- practical wisdom about teaching the modeling arts, including exercises that can actually accelerate learning the extremes of conceptual and technical skills modeling requires and projects that are so well designed that they move people rapidly toward self-sufficiency
- group model building and model use techniques that can move modeling out of the closet and directly involve policy makers

4 The Forrester awards include Roberts et al. (1983), Richardson and Pugh (1981), Aracil (1981) and Mosekilde (for advances in complex nonlinear dynamic systems, e.g., Mosekilde et al.1985), Morecroft (1985), Richmond (for STELLA and its manuals and teaching materials), Sterman (1989a,b), Senge (1990), Richardson (1991), and Abdel-Hamid and Madnick (1991). Other award-winning system dynamics works include Cooper (1980), Roberts and Dangerfield (1990), and .Reagan-Cirincione et al. (1991).

New practitioners would find the wisdom and best practice in the field hard to find. Armed with the apparent power of deceptively simple iconographic modeling software, they might not even know to look. And sadly, there is no sure sense of agreement on what constitutes great work in the field.

The difficulties of identifying and locating the best practice is potentially a serious problem that threatens the future of the field, as the best practice is swamped by the enthusiastic work of legions of new practitioners unfamiliar with the field's forty years of experience. We must also grant a flip side to the problem: the difficulty of identifying and locating the best innovative practice achieved by people who bring new perspectives, skills, and applications to the field.

The field needs a way of identifying, accumulating, and promulgating best system dynamics practice. One could imagine an edited volume on the state-of-the-art that is compiled under the direction of the the System Dynamics Society and is rewritten, say, every five years in a way that updates and accumulates the field's best practice and wisdom. A journal captures the *flow* of best written practice; we require a way of capturing the *stock*.[5]

Advancing practice

The field of system dynamics abounds in good introductions to modeling; it lacks second and third level workshops and texts that move practitioners to the most advanced levels of knowledge and skill.

It has been repeatedly observed that we have a number of reasonably good introductory texts in the field, but no text goes much beyond introductory material. Yet introductory texts continue to be produced. And unfortunately, all current texts are tied to particular simulation languages. The impression of our published teaching materials is that there is not much to know beyond stocks, flows, feedback loops, and software details, and whatever there is to know is tied to particular software, not to general insights and skills about modeling.

It seems obvious that the lack of advanced texts and workshops in modeling for policy analysis is a serious threat to the future of the field. Practitioners who manage to advance to extremely high levels of expertise do so either in the few University contexts where advanced courses are taught or colleagues collaborate, or they reinvent themselves and the field on their own. Reinvention is time-consuming and fraught with peril. Stinchcomb (1968, 143) said it best: "Explicit knowledge accessible to intelligent beginners is obviously more efficient for a science than knowledge perceived by the intuition of its geniuses."

The solution is clear, even if untried: we require advanced modeling texts, preferably written collaboratively to capture rich pictures of the arts of model-based policy analysis. Essential bibliographies are a start (e.g., Sastry and Sterman 1993), but the future of the field requires the integration of advanced skills and understanding in excellent teaching materials.

[5] The increasing use of the Internet for scholarly conversation and communication vividly illustrates the *flow* of ideas and the difficulty of accumulating a *stock* of the best ones.

Accumulating results

How can work in the field be organized so as to accumulate and promulgate widely accepted understandings of the structural causes of dynamic behavior in particular systems?

In addition to shared principles of wise practice, one of the hallmarks of a science is the accumulation of shared understandings with predictive power. After forty years it is fair to observe that the field of system dynamics has not come far in accumulating such results. For example, research and model building in economic dynamics have been ongoing in the field since the mid 1970s, yet how many scholars and practitioners who identify with the field can list the structural mechanisms underlying the various business cycles? Who has replicated the work of the MIT group in this area? Work in project management, ranging from Roberts (1963) to Abdel-Hamid and Madnick (1991), fares somewhat better in this regard, but what is the list of dynamic insights about project management that the field has accumulated? Work in economic development has been ongoing for more than a decade in the field (e.g., Saeed 1991, 1994), but again it would be difficult to list the insights or identify scholars who have worked to test and replicate results. On a different scale, many of us have simulated the Lotka-Volterra equations in introductory work, yet how many know Volterra's principle that stems from this simple dynamic system and how many of those can say how far the insight can be pressed? Finally, a number of dissertations have made significant advances in particular areas of application, but have failed to become common knowledge among scholars and practitioners in the field. (Any list of examples I would write would prove the point two ways: by illustrating some the reader is not familiar with and by leaving out some the reader believes should be listed but I do not know about.)

To advance beyond a craft, to approach the rigors of a science, the field of system dynamics needs to find ways to facilitate the accumulation of reliable results. Accumulating wise practice is crucial for maintaining high quality work in the field as practitioners enter and leave, but accumulating wise, replicated, and accepted results is essential for growth of understanding.

The future of the field requires mechanisms that can help avoid reinventing previous work or previous insights, and that can help scholars and practitioners to build on previous work and add to previous insights. Part of what is required is a *culture of accumulation* accepted by those who identify with the field. Much like a well formulated dissertation, every article and book that can be linked to previous work should trace its lineage and identify the foundation that it builds upon. In a spirit of cooperative, creative scholarship, published work should be replicated — tested in various ways for consistency, reliability, and extensibility — and the results added to a known and growing body of literature in each applied area.[6]

The accumulation of results in the field has been helped greatly by the system dynamics bibliography available on disk from the System Dynamics Society.[7] Accumulation of results is so crucial for the future of the field that I am prompted to suggest that the bibliography ought to be a

[6] We must acknowledge that there are forces inherent in scholarly activity that work against such cooperative creative scholarship, in particular the scholarly need to carve out areas of individual expertise that identify one as the expert in an area. Replication of previous work that "merely" adds confidence to the work and results of others is often not valued in the social sciences.

[7] Write to Ms. Julia S. Pugh, System Dynamics Society, 49 Bedford Road, Lincoln, MA 01773.

major ongoing work of the Society and the disks should be sent free to every member of the Society every one or two years. The bibliography is not evaluated, however; it indescriminantly mixes great and not-so-great work which may not stand up under deep scrutiny or replication. Perhaps the bibliography could begin to include evaluative comments by people who have reviewed or tried to replicate the work.

The mechanisms for accumulating results could include requiring students to replicate and if possible improve existing work and publish the results as Notes in the *System Dynamics Review.*

But in addition, we require more attention to the *packaging* of results so that they can be easily assimilated and passed along. The systems archetypes are a brave attempt in this direction, but more is required, particularly in formally linking the structure and dynamics of results in particular applied areas.

Making models accessible

How can formal models be designed, formulated, and presented so that they are accessible to the widest possible audience?

It has be said that an advantage of formal models is that they are explicit (Forrester 1961, Richardson and Pugh 1981). In contrast, it is said, mental models contain unstated assumptions and leaps of logic and intuition that force important aspects to be implicit. It has also been said that most formal models of any significance are too complex to be accessible to all but a tiny minority of modeling experts (Greenberger, Crenson, and Crissy 1976). We must admit the latter claim is probably true: as an illustration, recall that a technically gifted critic of Forrester's *World Dynamics* (1971) found it necessary to simplify the model to understand it sufficiently to argue his criticisms (Nordhaus 1973). The difficulties authors of articles in the *System Dynamics Review* have in presenting complex models in understandable ways provide further evidence for the significance and extent of the problem. We must acknowledge that in practice formal models, like mental models, have a necessary implicitness, which stems from their size, complexity, and algebraic formalisms.[8]

There have been instructive, even noble efforts to make complex models accessible: Forrester's *Urban Dynamics* (1969) and *World Dynamics* (1971), differed markedly in size and complexity but were presented in much the same way -- important stocks and flows, examples of crucial feedback loops, usually the positive ones, and examples of typical structure, followed eventually by a detailed, equation-by-equation explanation/justification.

Another approach involves the use of sector overviews keyed to model equations and coupled with diagrams detailing important microstructure; a typical example is Sterman and Richardson (1985). The use of sector overviews seems certain to become more widespread now that STELLA/iThink

8 The simulation methods and tools we use undoubtedly also impose hidden assumptions. What assumptions are hidden, for example, in the fact that our simulation languages are structured to simulate systems of the form **dx/dt = f(x,p)** but do not handle easily systems involving partial derivatives of variables other than time? What assumptions are hidden in the fact that we can not simulate a loop without a level in it or that graphical functions are limited to functions of one variable?

contains an overview layer that links in a meaningful way to the layer containing detailed model structure. Yet STELLA/iThink overviews do not easily allow the labeling of elements of structure so they, too, quickly become complex diagrams conveying little more than gross connections among amorphous sectors.

In a computing environment one could imagine model documentation that is organized as a collection of hypertext and hyperdiagram documents. The reader could click to activate a hyperlink from one level of documentation to the next, enabling an orderly exploration from overviews to model detail at the level of equations and even to explanations of items within equations. While clearly possible with today's technology, it is not clear what circumstances would call for such hypertext documentation nor what principles should guide its construction. We have only intuitive notions of what makes technical presentations accessible, and undoubtedly what works for one reader could fail for another.

Our intuitions about presentations that make models accessible needs to move toward a science of model documentation. It is an important area -- inaccessible models are barriers to understanding and will become barriers to both the growth of the field and the spread of policy insights stemming from insightful modeling efforts.

Qualitative mapping and formal modeling

What are the wise uses of qualitative mapping approaches, and what are the conditions that require formal, quantitative modeling?

Literature in the history of feedback thought repeatedly contains the assertion that formal, quantitative models are essential for understanding the dynamics of complex systems (see Richardson 1991 for examples). At the foundation of the field of system dynamics is the presumption, which seems to be repeatedly reaffirmed in the practice of applied policy modeling, that the dynamic implications of even moderately complex circular causal structures are impossible to discern without the aid of formal models.

Yet the field is experiencing the increasing use of qualitative tools — word-and-arrow diagrams under various labels (causal-loop diagrams, influence diagrams, cognitive maps), systems archetypes, and other approaches and techniques that fall under the general rubric of qualitative systems thinking. The relationships between these qualitative practices and the quantitative core of the field of system dynamics are unclear. Some hold that qualitative systems thinking tools have their place as precursors of formal modeling . Others contend that various qualitative approaches can stand by themselves and lead to reliable policy insights without formal, quantitative modeling.[9]

The history of feedback thought in the social sciences (Richardson 1991) does not hold out much hope for this latter point of view. The cybernetics movement began in the 1940s with considerable emphasis on circular causal processes, expressed qualitatively in maps and words, but rather soon turned its focus away from feedback loops to questions of coding, languages, and computing machinery. Initially subtitled "control and communication in the animal and the machine," the field

[9] For a range of examples and opinion, see "Systems Thinkers, Systems Thinking," special issue of the *System Dynamics Review* (10,2-3, Summer-Fall 1994), G.P. Richardson, E.F. Wolstenholme, and J.D.W. Morecroft, eds.

of cybernetics came to see its greatest promise in the study of communication. Feedback loops were largely lost in the shuffle, to the extent that most modern social scientists and folk in the street do not make use of circular causal patterns of inference. Given the difficulty of making reliable qualitative inferences from moderately complex circular causal maps, it is reasonable to suggest that the movement away from feedback analyses stemmed at least in part from the lack of what Forrester later supplied — tools and techniques (and a perspective) for building mathematical models of realistically complex circular causal systems and inferring their behavior through computer simulation.

Armed with almost forty years of experience simulating circular causal systems, some practitioners are embracing qualitative approaches. Their work holds promise because it is based on insights and patterns of thought that have been formed by years of modeling experience. Senge's system archetypes, for example, include insights that were first identified by Forrester in *Urban Dynamics* (1969) and stemmed from his model-based work up to that point. Most of the archetypes are model-based (although many practitioners would find it difficult to build formal models of the archetypes — see Dowling, MacDonald, and Richardson 1995).

Yet readers of this qualitative work do not know of its quantitative foundation. They are encouraged to apply qualitative feedback maps to understanding puzzling and complex management problems. Given the history of feedback thought in the social sciences, that trend is worrisome. The history suggests that inferring dynamic behavior from word-and-arrow maps involving circular causality comes only in two situations, when the map is a recognized structure previously verified by simulation, and when the map is extremely simple. Yet modelers and nonmodelers are encouraged by our recent qualitative trend to try to learn from the application of new qualitative maps to new situations.

The trend toward the use of qualitative word-and-arrow maps for dynamic analysis raises several research questions whose answers may be crucial for the future of the field. What are the system conditions that suggest that a qualitative mapping approach can produce reliable inferences? What are the conditions under which a qualitative mapping may yield unreliable or false inferences? Are word-and-arrow maps showing explicit stocks and flows more reliable, although less accessible, for various practitioners or audiences? What are the implications of packaging systems insights in systems archetypes? Do archetypes limit or expand people's capabilities to reason in circular causal settings? Finally, is it possible to state conditions under which qualitative maps are best employed and other conditions which require quantitative modeling?

The field must address the relationships between qualitative mapping and quantitative modeling — in short, when to map and when to model. To advance in this area the field requires both academic research and reflective, constructively self-critical practice.

Widening the base

The future of the field of system dynamics rests on our abilities to widen its base, the population understanding the significance of feedback and circular causality in living systems.

Ever since Forrester (1971b), it has been common within the field to assert that the behavior of complex social systems is counterintuitive. Critics have noted with considerable offense that it sounds like system dynamics devotees are saying "counterintuitive to everyone except us." That is a fair criticism: deep down, the counterintuitive claim rests on the often puzzling dynamics that a nonlinear feedback system can exhibit and which can only be reliably drawn out and understood with the aid of simulation models of the sort that system dynamicists build. To increase the acceptability of results from excellent and often counterintuitive system dynamics studies, it is essential for the field to widen the base of people prepared to receive difficult messages about the behavior of living systems.

Toward this end, two kinds of current work are exemplary: the journalism of Donella Meadows (1989, 1991) and bringing systems thinking and system dynamics modeling to school children (see, e.g., Brown 1992 and *Systems Thinking in Education,* special issue of the System *Dynamics Review* 9,2(summer 1993)). Meadows's writings are the best work I know of related to the field of system dynamics striving to reach a lay audience. She aims not at modelers or scholars but at thoughtful readers of all sorts and backgrounds and educational levels. She is almost alone in this endeavor, however.[10] To widen the base for system dynamics work, more efforts like hers must appear.

Bringing systems thinking and system dynamics in accessible forms into elementary and high schools is also a major step forward for the future of the field of system dynamics. Those at the forefront of this effort in the United States are school teachers, aided and abetted richly by Barry Richmond and colleagues at High Performance Systems and a few other system dynamics professionals. Scholars and practitioners in the field need to recognize the importance of these efforts. If extended, they promise to widen dramatically the population ready to hear, understand, and act on messages like "worse before better behavior," and to accept the policy implications of "tragedies of the commons."

These efforts to widen the base deserve the help of scholars and practitioners in the field. Far from being diversions, these efforts to expand the dynamically wise population are crucial for the future of the field of system dynamics.

Confidence and Validation

What are appropriate procedures and standards for establishing user confidence in system dynamics models in various decision environments?

In 1980 Forrester and Senge published a classic statement on model validation and the development of user confidence. Examining the triple relationships of model structure, model behavior, and linkages between structure and behavior, they proposed a suite of seventeen separate tests that can be used ensemble to establish user confidence in system dynamics models.[11] More importantly, they confronted the notion that one or several simple tests, such as classic statistical

10 I believe Jørgen Randers in Norway has made similar journalist efforts but I do not know any details.

11 See Richardson and Pugh (1981, 310-320), which organizes a number of the Forrester and Senge tests into tests focusing on structure and on behavio. The question of model validity is cast in terms of the model's *suitability* for its purpose and the problem it addresses, its *consistency* with the slice of reality it tries to capture, and its *utility and effectiveness*.

goodness of fit tests, could not serve as a single and uniform path to model validation. While a number of specific papers have followed up on aspects of this work (see, e.g., Sterman (1984), Barlas and Carpenter (1990)), it seems sadly clear that the most comprehensive statement on model validation and user confidence in system dynamics models is still a single paper that is nearly twenty years old.

The field critically needs to return to the central issue of model evaluation and unpack it into its several constituent parts. System dynamics models are now being constructed to support planning and decision making in a wide range of decision environments. Models built to support testimony in court should surely adhere to different confidence and validity standards than those used to inform the strategic thinking of a small corporate board of directors. Similarly, models that support public infrastructure planning efforts will meet a different level of scrutiny and review than will those supporting policy development in a legislative environment (see Andersen 1991). Hence, it seems that a necessary first task in advancing our thinking about model confidence and evaluation is to craft a fairly comprehensive taxonomy of decision environments so that a more detailed discussion of validation procedures and tests can become more focused and fine-grained.

As a next step, the field needs to arrive at greater consensus concerning what types of confidence building and validation procedures and tests are more appropriate in what types of decision environments. For example, Forrester and Senge's "surprise behavior" test or the "mistaken identity" behavioral test may be an extremely powerful way to build confidence when working with a small executive group who share a point of view about the problem being studied but may have little power at all in more public decision making environments. We need to accumulate wisdom about under which conditions do various types of tests and procedures appear to be most appropriate.

Finally, our list of appropriate tests for building confidence in system dynamics models needs to be expanded and software and other more automatic procedures need to be invented to implement our most commonly used evaluation tests, such as the reality check feature of Vensim (Peterson and Eberlein 1994). For example, Reagan-Cirincione et al (1991) proposed a simple "complete the graph" exercise in which a group of managers were asked to sketch the completion of an interrupted time series simulation under various policy changes. By comparing what managers thought would happen in the system to what the simulation predicted would happen, managers were able to engage the relationships between model behavior and model structure (and hence policy changes) at a deeper level. This proved to be a powerful test that could be more formally developed and software could be easily constructed to generalize the application of a test such as this one.

The use of formal models to aid policy understanding requires a rich and diverse mix of procedures to establish confidence in model-based analyses. The future of the field requires ongoing attention to the question of model validity.

Summary and Challenge

This note has identified eight problems for the future of the field, ranging from problems specific to the field of system dynamics to problems of more general concern in any scientific discipline.

The identified problems and questions are:

1. *Understanding model behavior:* The principal outstanding technical problem in simulation modeling is the development of tools to aid understanding model behavior.

2. *Accumulating wise practice:* The field of system dynamics needs improved mechanisms for accumulating and promulgating insights about wise modeling practice.

3. *Advancing practice:* The field of system dynamics abounds in good introductions to modeling; it lacks second and third level workshops and texts that move practitioners to the most advanced levels of knowledge and skill.

4. *Accumulating results:* How can work in the field be organized so as to accumulate and promulgate widely accepted understandings of the structural causes of dynamic behavior in particular systems?

5. *Making models accessible:* How can formal models be designed, formulated, and presented so that they are accessible to the widest possible audience?

6. *Qualitative mapping and formal modeling:* What are the wise uses of qualitative mapping approaches, and what are the conditions that require formal, quantitative modeling?

7. *Widening the base:* The future of the field of system dynamics rests on our abilities to widen its base, the population understanding the significance of feedback and circular causality in living systems.

8. *Confidence and validation:* What are appropriate procedures and standards for establishing user confidence in system dynamics models in various decision environments?

No doubt these are not the only problems in the field. Certainly, for example, the difficulties of system conceptualization place that topic high on anyone's list of significant problems facing both new and experience practitioners. And although I have offered arguments for the significance of these eight problems for the future of the field, I acknowledge that some may be able to identify other, more pressing problems or in other ways extend and improve this list. In fact, I invite readers to do just that.

But a list is a start and the battles can now be joined. For the goal of such a list of outstanding problems for the future of the field is a concerted effort by many system dynamicists around the world to address and solve these problems.

As we continue to employ our simulation arts and a dynamic, feedback perspective to address the most significant problems the real world presents us, let us also address these outstanding problems our field presents us.

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