IS SYSTEM DYNAMICS THEORY COMPLETE?--EXTENSIONS AND INTERFACES

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ABSTRACT

System dynamics consists of a body of theory, philosophy, methodology, policy-related applications, and experience. Basic to system dynamics is the theory of the semi-closed, fully closed-loop system in which the feedback loop is the principal construct. In the 20 years of its existence, major emphasis has been placed on the methodology of model-building, on applications, and on philosophical debates involving alternative approaches, particularly the static econometric approach. Experience has produced improvements in the original theory. However, feedback loops are not the only constructs for dynamic theory-building, and cybernetic, self-regulating systems are not the only kinds of living systems, nor is the cybernetic perspective invariably the only or most appropriate perspective over the life history of a particular system. The processes of self-organization and the emergence of new structure deserve equal attention in the evolution of systems.

This paper briefly reviews the history of system dynamics. An analysis is then made of present system dynamics theory. This is followed by summaries of three field theories--of critical phenomena, catastrophe theory, and dissipative structures--and attempts at synthesizing these theories and system dynamics. Then ways of enrichening existing system dynamics models with fuller use of knowledge from behavioral/social science and sociotechnical systems, with particular relevance to the National Model, are discussed. The paper concludes with an identification of three immediate next steps in research.

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INTRODUCTION

It is now 20 years since the appearance in 1961 of Jay W. Forrester's Industrial Dynamics [7]. System dynamics theory is the outgrowth of a marriage among cybernetic (information-feedback) theory, practical experience with the management of large organizations, and the computational power of large digital computers. The early use of system dynamics models, based on the original theory, in turn generated further theory about the behavior of complex systems and organizations, especially in the context of policymaking. This secondarily-derived theory includes the well-known counterintuitive behavior of complex systems, resistance of behavior to most parameter changes, unexpected sensitivity of behavior to some parameter changes, etc. It would appear, however, that advances in the theoretical underpinnings of system dynamics modeling have been few in recent years.

Nevertheless, over the years a number of real or imagined limitations have been ameliorated. For example, statistical methods like GYPSIE have been developed for system dynamics models. Probabilistic system dynamics is an interesting blend of a system dynamics model with a FORTRAN-based event-on-trend, event-on-event, and trend-on event cross-impact model.

Much of the debate expressed in the large literature, though, seems to be framed as follows: given the basic theory of system dynamics, let us concentrate on the methodology. The fundamental question as to the completeness of system dynamics (or alternative) theory remains unanswered. Little argument can be presented against the pervasiveness of feedback processes in both living and nonliving systems. Feedback processes, however, are not the only processes immanent in these systems. Thus, the basic cybernetic theory of which system dynamics is one important part is excellent for describing how systems behaved the way they did in the past, behave the way they do now, and will behave in the future--given the same kinds of historic or ongoing processes that change only quantitatively. System dynamics cannot handle emergence, that is, qualitative reconfigurations or non-preprogrammed changes in patterns. Neither can any other large computer-simulation methodology. The theory of emergence is just now being developed.

The present author hypothesizes that the evolution of physical, biological, and social systems is characterized by stages in which different kinds of processes may be predominant. These stages differ by: (1) the rates of change, for example, quasilinear, exponential, or hyperbolic; (2) the creation or destruction of order or form (anabolic and catabolic morphogenesis); (3) the relative importance of deterministic versus stochastic factors; (4) the kind of dynamic process that is dominant; and (5) the qualitative nature of the emergent pattern. In short: these systems are both self-regulating systems and self-organizing systems, and dominance of a given kind of process differs according to evolutionary stage. System dynamics at present does not appear to be equipped to deal with the different stages of evolution even though Forrester and others

(including the present author) believe that the world has entered a stage of major transition or transformation. Thus, system dynamics societal systems models must be geared to a fuller range of processes if they are to have the desired effectiveness in futures research, long-range planning, and policymaking.

A great deal of effort has in particular gone into the comparison of system dynamics with econometrics/regression analysis. The present author accepts the superiority of system dynamics but asks: given the emphasis of the dynamic over the static, whither now?

The next section discusses a number of apparent limitations of system dynamics theory. In the third section, particular emphasis is placed on critical phenomena, catastrophe theory, and the theory of self organization (theory of dissipative structures) under conditions far from equilibrium. Considerable attention is paid in the fourth section to the need for better understanding of behavioral/social science and sociotechnical processes and constructs. Ways in which these theories can enrichen system dynamics, as well as possible irreconcilable differences between system dynamics and alternative dynamic theories, are considered throughout the paper. The fifth and concluding section presents suggestions for further research.

This article represents a continuation of a long-term research effort directed toward societal and organizational systems theory-building and toward the improvement of computer simulation modeling used for long-range planning and policymaking. Several references present earlier thinking and a detailed coverage of the original literature [1], [2], [3], [4], [5], [6].

ANALYSIS OF PRESENT SYSTEM DYNAMICS THEORY

This section discusses areas that have not yet received much critically analytic focus and in particular areas that are directly related to the new field theories to be emphasized in the following section.

Exogenously versus Endogenously Induced Behavior

System dynamics stresses the closed-system or closed-loop-system characteristics of its models. Unfortunately, the thermodynamic term "closed" and the communications-theoretic term "closed loop" are often used interchangeably. System dynamics models cannot be closed, nor can any other model of complex systems because matter and energy cross the system boundary. Consider, for example, the cloud symbols representing sources and sinks. The external environment itself is ever changing; for instance, the flow of manpower changes qualitatively over time as a function of forces outside the system boundary. Most system dynamics models are, however, closed-loop systems in that no feedback loops are allowed to cross the system boundary. Exogenous variables, if used at all, are considered to be temporary pending further understanding of the real world.

This theoretic approach does not appear, however, to circumvent a more serious question concerning the origin, external or internal, of behavior in realworld systems. All systems can be affected by external perturbations or stimuli. But one class of systems, living systems, is capable of self-regulating, self-maintaining, and self-organizing behavior. System dynamics models apply to living systems and describe aptly most features of self-regulation and self-maintenance. Once the system boundary is determined and the

minimum number of relevant variables and feedback loops incorporated within that boundary, the system strives to regulate and control the interactions of its variables within tolerable limits and to maintain itself as a viable system in spite of external perturbations. Sometimes rates of change are so great or frequencies or periods of oscillations such that limits to the capability for regulation and control are exceeded, and one or more levels essentially collapse. But system structure does not change, nor do new behaviors arise spontaneously within the system. Thus, system dynamics does not capture the self-organizing properties of realworld living systems. Self-organization appears to be especially related to processes of fluctuation, threshold, and discontinuity.

Fluctuation

The term "fluctuation" is widely used in the literature of dynamic systems including the system dynamics literature. In system dynamics the term is applied both to the high-amplitude, low-frequency oscillations so characteristic of system dynamics models and to the exogenous random-noise inputs. But these applications capture neither the spontaneity nor the changes in likelihood in realworld systems, especially antecedent to reconfiguration. Contrast two realworld situations. In one case, frequencies of internal cycles in organisms are sensitive to and even become entrained with the frequencies of environmental stimuli. The deleterious physiological and performance responses of human operators to the frequency ranges of vibration and the many forms of biorhythms provide examples. This situation appears consistent with the system dynamics explanation of the effects of random noise on the system. The other case involves the appearance of genetic mutations and of human discoveries, innovations, and "great men." Consideration of the probability of occurrence, and the subsequent amplification or damping, of such fluctuations is of utmost importance to the evolutionary theory of organisms, organizations, and societies. Probabilities of occurrence do not appear to be constant over time or place and appear to speed up near critical points or thresholds. The fluctuations can be expressed in terms of much greater variety in sizes, structures, and behaviors. In addition, probabilistic behavior, once a critical threshold is exceeded, triggers deterministic behavior.

<u>Discontinuity</u>

Enough examples are now recognized from the behavior of nonliving systems and from organic evolution, human history, and current human individual human and societal behavior to characterize discontinuity as an inherent feature of system behavior. The importance of discontinuity to modeling theory appears to have been lost in the controversy between continuous and discrete schools of simulation modeling. System dynamics is a continuous modeling methodology utilizing differential equations approximated by difference equations so as to meet the requirements for discreteness in digital computers. System dynamics handles discontinuities in two ways: (1) by step-function inputs and (2) by CLIP functions internal to the model. But these means do not capture the poorly anticipated suddenness of realworld discontinuities. The step inputs mask antecedent changes, and the CLIP functions require preprogramming. Thus, while system dynamics realistically describes many aspects of past behavior, its usefulness as a predictive modeling methodology is still severely

constrained.

<u>The Continuity of Evolutionary and Historical Processes</u>

The concepts of stochastic evolutionary and historic stages intercalated with deterministic stages, discontinuity, fluctuation, and self-organization in open living systems suggest that, although there is continuity of basic processes across time in general, different periods exhibit a dominance of different processes. In other words, feedback dynamics cannot portray or substitute for the entire repertory of evolutionary/historic processes. Several observers have commented on the importance of recognizing stages of transition or transformation. System dynamics describes these stages well under certain circumstances, for example, in a world described by a logistic curve. A stage of slow, then rapid positive-feedback-based exponential growth is followed by a quasilinear stage in which the forces of growth conflict with the forces of competition, exhaustion, or negative-feedback-based regulation and control, which is in turn followed by a stage of growth the rate of which through regulation decreases toward some asymptotic value. Repeated competition between growth and regulation, involving two or more levels, of course produces the familiar oscillations of system dynamics models.

However, exponential, logistic, and sinusoidal constructs, for several reasons, do not accurately represent all reality. First, analysis of person-artifactsand person-innovations from the earliest Paleolithic to the present indicates that the rate of growth is hyper-exponential or hyperbolic rather than exponential. Second, the envelope curve of successive logistic stages shoots through the local ceilings or limits producing an acceleration of evolution and history. Third, the local stages of such intense interaction between society and technology are separated by platforms characterized by slight change and high degree of stability, and these platforms separate qualitatively different forms. These platforms therefore often represent discontinuities following the exhaustion of potential for further innovation. On the surface it may be quite difficult to differentiate between a period around the inflection point within a local logistic stage and a period of slow change between successive local stages. It may be likewise difficult to distinguish between a local limit to growth and an absolute limit described by the envelope curve.

Equilibrium

The concept of equilibrium is widely employed in the sciences in both the static and dynamic senses. In economics the concept has had a particularly invidious impact, for example, that supply will adjust or can be made to adjust to demand and vice versa. John Maynard Keynes stressed stimulating the growth of the economy (and the money supply) through increasing demand via government interventions and thereby reducing unemployment. Recently, he has become known as the "father of modern inflation." The present Reagan Administration speaks of supply-side economics. Presumably, removal of government regulations coupled with tax cuts, reductions of spending for supposedly unproductive purposes, and tight control of the money supply will provide the incentive for private business and industry to increase production so as both to increase the ratio of goods and services to money and to create enough new jobs significantly to reduce unemployment. Although these alternative policies have had and will continue to have a profound effect on the world

economy, they are based on limited and increasingly obsolete and inappropriate thinking and theory.

System dynamics deals with both equilibrium and disequilibrium conditions. Equilibrium is defined in terms of the equality of value of level variables, which is usually an initial condition or a condition when exploding oscillations and asynchrony among variables have been brought under control via the proper policies.

Even the system dynamics view may be limited, however. A system may display two or more levels or surfaces of equilibrium and may suddenly jump, drop, or flip from one level to another. There may be no transition into equilibrium. In some systems these changes are essentially irreversible, for example, in the case of species hovering around the threshold of extinction. Systems also can function far from equilibrium where the results of perturbations and fluctuations can be the emergence of qualitatively new structure. At a time of apparent societal transformation, socioeconomic policies intended to reestablish equilibrium between supply and demand may instead trigger massive and irreversible unemployment, destruction of natural resources, civil disorder, or war.

Complete equilibrium and stability are very likely not even desirable policy goals. They reduce system <u>resiliency</u> and therefore capability to learn and adapt [9]. Just how much slack to leave in the system hence becomes an important policy consideration.

The Time Frame of Models

System dynamics provides great flexibility in the choice of solution intervals and of total time simulated. Short intervals of seconds or subseconds can be applied to the simulation of metabolic and other physiological processes. However, social system models have typically involved total times of hundreds of years. These long run-times may be unrealistic for two reasons discussed above: (1) the question of qualitative continuity of evolutionary-historic processes and (2) the increasing evidence of world society's being in a stage of major transformation. If these points be granted, then it seems unlikely that the same variables will persist and that the same feedback loops will extend beyond the imminent discontinuities. One can think of many examples of recent or imminent system change where purely system dynamic models would be inappropriate--the Iranian revolution, the Polish worker strikes and the emergence of Solidarity and governmental reforms, the 1980 Miami race riots, the 1977 New York City power failure followed by blackout looting, the summer 1981 civil disorders in British cities, and the situation in American prisons and with the "criminal justice system" in general.

Given the immense turbulence of the world today, it would appear that the simulation run-time of the National Model should end around the year 2000. Deserving particular attention is the question as to whether the present world transformation, if that be accepted, can be portrayed solely by the concept of a downturn in a Kondratieff cycle. One must remember that the last downturn--the 1929 stock market crash and the Great Depression--was accompanied not only by an excess of capital, too rapid growth, a high degree of speculation, and other economic factors but also by dramatic social and political changes in the United States, Germany, Japan, Italy, and elsewhere. Some authors argue that only the quick, positive, and supportive actions of Franklin D. Roosevelt (a fluctuation of the "great man" kind) and his administration prevented a revolution in the United States.

Feedforward

Realworld systems show the capability to anticipate and to learn; hence, in many cases involving the future, feedforward may be a better construct than is feedback. Rational expectations theory in economics provides one example. People, once disappointed by government policies, anticipate and take counteractions against a repitition of these policies.

NEW THEORIES AND CONSTRUCTS

In the last several years theoretical advances in physics, physical chemistry, and topology have provided new insights as to how dynamic systems change structure and organization qualitatively. These advances stem from the study of: (1) critical phenomena in physics, (2) sudden changes beyond discontinuities (catastrophes), and (3) self-organization (dissipative structures) through fluctuations in open physicochemical systems far from equilibrium. Collectively, these developments represent advances in field theory, that is, the theory of how structure and behavior depend on the interplay of forces in a field rather than upon the specific properties of the elements of the system. Importantly, a number of theoretical interpretations of ecosystem and societal system evolution and behavior have been based on these theories and constructs.

Critical Phenomena

The critical phenomena are the qualitatively different organizations and behaviors on either side of a critical point or threshold, say, of a temperature. Examples include liquid-gas phase transitions, ferromagnetism, metal alloys, and miscible-immiscible fluids. Quite dissimilar substances display strikingly similar behaviors.

The most important construct that can be applied to complex biological and social systems is the critical point, usually a catastrophic point, and the nature and frequency of fluctuations in the vicinity of this point. Far from the critical point there is randomness, closer to the point short-range order emerges, and near the point occur a great number and variety of fluctuations, for example, in the scale of organization. Within a given scale of organization are included smaller scales, and in turn a given scale is incorporated into even greater scales. Local or short-range forces have produced long-range order (correlation), often through neighbor-to-neighbor impacts. This type of system change does not appear to involve feedback. In the case of a ferromagnet, all electron spins may be aligned so as to favor magnetism, but the system remains unmagnetized until after the Curie point has been passed from above. Thus, structural change is antecedent to behavioral change. The system is set to reconfigure but needs one last push.

Of course no serious systems theorist would propose a <u>reduction</u> of the behaviors of complex biological and social systems to laws governing only the particles of physics. Nevertheless, there does appear to be increasing evidence for the universal applicability of several natural laws to different hierarchical levels of organization of matter, energy, and information. But even if the construct of critical thresholds of qualitative reconfiguration turns out to be no more than a guiding metaphor when applied to biological and social change, its present heuristic value should be evident. Thus, at the phenomenological level, there do appear to be both a higher frequency, greater amplitude, and greater variety of fluctuations and of emergent forms now than was the case in the two decades or

so following the end of World War II. Empirical evidence for this increased intensity, pace, and variety of change can be seen in human life styles, religious beliefs, cults, drug use, book publishing, television, crime and violence, economic indicators, government changes, insurrections, land use, and species brought to the brink of extinction. A simple list of course says nothing about the causal nature of each phenomenon or event. One could construct all sorts of diagrams showing mutual causality among these and other phenomena, but the diagrams could misrepresent the real world greatly because the causal pathways are open-loop and irreversible or because the listing gives symptoms rather than underlying causes. Some quite serious world changes are in these categories. Land use and abuse exemplifies the former. Land use produces habitat destruction, which yields species extinction with no feedback loops involved. In the second case, the underlying force may be cultural old age and exhaustion, with the fluctuations' representing the erosion and breaking of restrictive bonds in the decaying culture and both last-gasp efforts to preserve the old and the germs or nuclei around which is built the new configuration.

<u>Catastrophe Theory</u>

Catastrophe theory is a means of showing how slight incremental changes in one or more continuous variables (independent variables, causal factors, control factors) produce sudden discontinuous jumps or drops in one or more behavior (dependent) variables. A number of different catastrophes have been identified. The "elementary" catastrophes are classified by the number of control and behavior factors each possesses. The fold (one control and one behavior factor), the cusp (two control factors and one behavior factor), and the butterfly (four control factors and one behavior factor) have been used most, especially in the behavioral/social and biological sciences.

Figs. 1 and 2 further illustrate some principles of catastrophe theory and its interface with system dynamics.

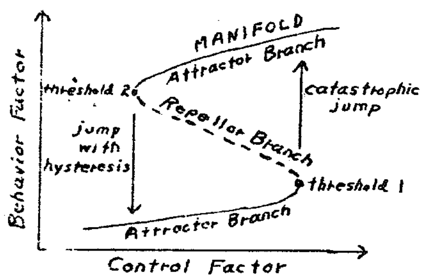


Fig 1. Fold Catastrophe

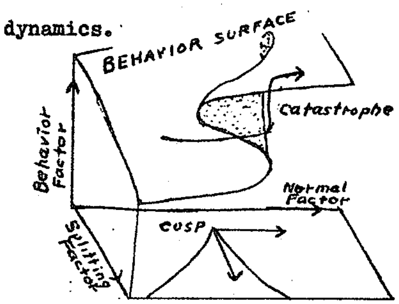


Fig 2. Cusp Catastrophe

Fig. 1 shows the simplest catastrophe, the fold. The manifold represents equilibrium points of maxima or minima (the attractor) separated by points of minima or maxima, respectively (the repellor or inaccessible region). The fold (and also the cusp) can be shown to evolve from the logistic curve. Positive feedback may contribute to the growth shown on the lower limb and to the decline shown on the upper limb, but regulatory negative feedback is involved insignificantly if at all. When the magnitude of the behavior variable reaches the singularity on either limb, behavior jumps or drops discontinuously to the other limb. Further, the system dynamics practice of averaging (as well as the econometric practice of finding the line of best fit by regression analysis) would be highly inappropriate in such situations. The average or best-fit line could lie in the repellor region, the <u>least likely</u> behavior.

The cusp catastrophe is a particularly useful construct because it includes a family of sub-constructs. If one observes one of the latter, a clue is provided for search for the others. The

five sub-constructs are: (1) bimodality of behavior in part of the range, with sudden jumps from one mode to the other; (2) hysteresis or path non-reversibility in jumps between modes or sheets; (3) an inaccessible or repellor region on the behavior axis, representing least likely behavior; (4) divergent behavior on either side of the fold on the behavior surface, so that a small perturbation in the initial state of the system may produce a large difference in the final state; and (5) the catastrophic jump itself.

The cusp catastrophe provides further insights as to how a modified system dynamics might better mimic the real world. Sudden fads, religious conversions, and political switches, social behaviors quite important to policymaking, appear better depicted by the bimodality of behavior with sudden jumps from one mode to another than by the continuous oscillations of system dynamics levels and rates. The last-minute switch from Carter to Reagan in the 1980 presidential elections may have represented such a catastrophic jump. Hysteresis can be viewed as a delay or inertia in the system, but hysteresis does not appear to be isomorphic to any system dynamics delay because the jump and fall pathways are qualitatively and quantitatively different. In some cusp models the two sheets of the behavior surface represent polarizations or qualitatively different system states, for example, dove and hawk attitudes. In other models, the two sheets represent different scales of the same variable, for example, numbers of spruce-budworm larvae in Canadian forests. The last case would apparently require inserting a delay within a level.

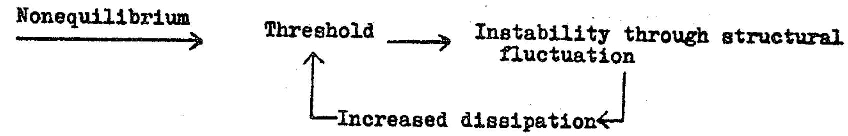
Some of the most powerful sub-constructs of the cusp catastrophe are the concepts of attractor, repellor, divergence, and splitting. These concepts can aid the modeling of competition, conflict, polarization, and evolution of new forms, which are almost inherent in most behavioral/social and ecological situations. For example, fear and rage may be conflicting emotions influencing aggressive behavior. Divergence and splitting may lead to new system forms as in speciation.

In Zeeman's model of a stock market crash [13], the normal factor is excess demand for stock (which could be a system dynamics level variable), the behavior factor is the rate of change of the price index (which could be a system dynamics rate variable), and the splitting factor is the proportion of the market held by speculators as opposed to long-term investors (which could be a level variable, but which would be difficult or impossible to enter causally into a system dynamics model). Increase in the splitting factor causes greater and greater divergence between the top (bull market) and bottom (bear market) sheets; that is, the larger the splitting factor, the more severe the crash. The slow smooth recovery involves positive feedback loops in which the behavior factor affects the control factors. Once again, it appears that catastrophes occur in the absence or exhaustion of negative-feedback regulation and control. When equilibrium breaks down, catastrophes follow.

System dynamics and catastrophe theory have two important properties in common: (1) determinism and (2) equilibrium. These features could start the melding of the two basic constructs.

Dissipative Structures

Dissipative structures are self-organizations arising through the occurrence and amplification of certain fluctuations in systems operating far from equilibrium. The basic dynamics are as follows:



Instability, triggered by nonequilibrium conditions, maintains a continuous energy dissipation (measurable by entropy production in physicochemical systems), which further increases the level of dissipation, leading to further instabilities. Prigogine [10] calls these processes evolutionary feedback. Nonequilibrium conditions lead to exceeding a threshold, which now increases instability by means of structural fluctuation, which in turn produces increased dissipation. The last, in a feedback loop, modifies the threshold, leading to evolution through a succession of transitions.

Most of the theory of, and experimential substantiation for, dissipative structures comes from physical chemistry. However, Prigogine and his associates, incorporating research ideas from workers in several fields, have extended the theory to ecosystems and societal systems. One example is the oscillation between "autocratic" and "democratic" social structures among the Kachin tribes of northern Burma. When the prestige of a new chief is larger than dissatisfaction with his ascension, the autocratic regime remains stable. But if dissatisfaction is greater than prestige, entry into the system of a few rebellious persons drives the system to a revolutionary state as the number of rebels increases explosively.

Cybernetic theories like system dynamics and control theory do very well in describing self-regulation and why ecosystems and societies stay the same, but they do not describe well how these systems change into new forms. Once again, in evolution equilibria are not maintained but are destroyed. A system, subjected to a field of external and internal forces that collectively surpass some threshold, ruptures and/or yields emergent new forms. As long as the boundary of stability is not passed, the system will return to essentially its equilibrium state if the external perturbations and internal stresses and strains abate. System equilibrium, stability, instability, collapse, and emergent organization thus are functions of the intensity and persistence of the given field of forces. There are many realworld examples of systems that do not return to equilibrium following removal of a perturbation. Holling [9], for example, discusses the extinction of several species of commercial fish in all five Great Lakes. Even when fishing pressure was removed, the fish did not return. It is the belief of the present author that the same dynamics apply to modern Western society, producing new structural forms like the chronically unemployed, underemployed, and hopeless.

System dynamics models do not exploit sufficiently the concepts of domain and boundary of stability, that is, behaviors at the extremes of oscillations or fluctuations beyond which the system cannot return to its original condition. The adaptive capabilities of systems are sorely taxed under conditions near stability boundaries as established functions and policies fail to perform their corrective actions. Although programs and policies, for example, a training program, a birth control program, or a technological breakthrough, may be introduced exogenously at later times in a system dynamics simulation run, these policies operate through the pre-set system structure and do not capture the breakdown of system structure and emergence of new structure under conditions far from equilibrium. For example, the analysis of the Kondratieff cycle in the

National Model should focus not just on apparent causal factors such as an excess of capital, on the quantitative features of oscillations, and on presently apparent corrective policies, but also on the emergence of new kinds of structure. A retrospective and retrodictive qualitative analysis of new forms emergent during the late downswing-early upswing phase of past Kondratieff cycles could contribute greatly both to theory-building and to policymaking. Evolution in general proceeds in the direction of greater complexity, with each stage representing a successive reequilibration to changing forces. As emphasized throughout this paper, it is the critical intervals between stages, such as the present one, that should receive our greatest attention.

Toward a Melding of System Dynamics and Complementary Perspectives

As a point of focus, consider the anthropological study of the New Guinea Tsembaga tribespeople by Roy A. Rappaport. Rappaport emphasized the self-regulating function of ritual in this society. Other, evolution-oriented anthropologists, however, have criticized Rappaport's interpretations on the basis that they explain social stasis but not social change. Systems ecologists have interpreted the study in terms of a society's maintaining fluctuations so that the stability boundaries do not contract and thereby reduce the capability to respond to unexpected perturbations and in turn reduce survivability.

Shantzis and Behrens [12] designed a system dynamics simulation model based mainly on Rappaport's Pigs for the Ancestors. The model included critical levels or thresholds for pig-person competition (social temperature or conflict to other authors) and for the amount of human labor required to tend a given number of pigs. These critical levels, via a CLIP or FIFGE function, triggered festival and warfare behavior in which many pigs and some people were killed, thus restoring human population and pig population to equilibrium levels consistent with land carrying-capacity.

This model therefore simulates some features of a catastrophic jump. Indeed, one could envision an alternative catastrophe theory model with pig numbers and human numbers as control factors and human aggression as a behavior factor.

ENRICHENING SYSTEM DYNAMICS—BEHAVIORAL/SOCIAL/SOCIOTECHNICAL THEORY

Within the scope of present system dynamics theory, great strides can be made toward greater fidelity through the better understanding and incorporation of theories and findings from psychology, sociology, cultural anthropology, and the study of sociotechnical systems. Table 1 gives some representative constructs.

Table 1. Representative Behavioral/Social/Sociotechnical Constructs

Perceptual	Motivational	Social
Attention	Aspiration	Competition
Bias	Conflict	Conflict
Gestalt	Drive	Contagion
Saturation	Frustration	Diffusion
Stimulus strength, duration	Gap	Movement
	Hierarchy	Role
Cognitive	Incentive	Social comparison
Attitude	Need	Social temperature
Attribution		
Belief	Emotional	Cultural
Comparison	Aggression	Established practice
Creativity	Alienation	Ethnic difference
Decision	Helplessness	Mores
Dissonance	Hostility	Political philosophy
Expectancy	Nonrationality	Religious difference
Imagination		Sex difference
Intelligence	Activity	
Judgment	Achievement	Sociotechnical
Learning	Acqusition	Autonomy
Memory	Consumption	Innovation
Symbolism		Discovery, invention
Thinking		Participation
Value		Technological impact
		Work system

Most of the areas have been studied by disciplinary specialists and apply to several hierarchical levels of living systems. Unfortunately, the specialists have provided few if any grand theories recently and few if any "off-the-shelf" models for ready incorporation into system dynamics theory and models. This does not, however, justify the practice of some system dynamicists of aggregating and masking these factors in averages, delays, or purely economic variables. Table 1 is meant to be both a source of new insights and constructs and a source of caution that system dynamics theory and practice applied to socioeconomic systems will fail to represent the real world in the absence of these factors. In many cases using these factors is straightforward; for example, level of aspiration, level of expectancy, and social comparison between these levels and actual achievement lend themselves directly to system dynamics modeling.

Because of the criticality of societal problems at the national and international levels, and because of the potential helpfulness of the system dynamics National Model in the solution of these problems, the remainder of this section will be devoted to work, employment, nonemployment, and productivity. Here motivational and sociotechnical theory and findings can most meaningfully be contributed. In keeping with theories discussed earlier, it is collective rather than individual behavior that most demands our attention.

A Look at the National Model

Consider first the basic structure of the labor and production sectors of the National Model. Unless recent modifications have been made of which the present author is unaware, the basic structure of the labor sector is as follows [8], [11]. The sector possesses a level or pool of the general nonemployed, a level or pool of the nonemployed for each industrial-production sector, a level or pool of the employed for each production sector, a level of wages, and five rates, namely, departures from the sector and arrivals in the sector connecting the first two levels, separation rate and hiring rate connecting the second and third levels, and change in wages accumulated as wages.

A number of ways in which the model might be improved by considering behavioral/social and sociotechnical factors can be summarized as follows:

1. There is no simple relationship between wages and work performance. Assembly-line workers, among the most highly paid blue-collar workers, are also among the most alienated. Work fulfills other functions beyond earning money. Money has a symbolic meaning transcending purchasing power and consumption. People make trade-offs among the various positive and negative incentives ("valences") of a job and among work and non-work factors. Values and attitudes toward work have changed greatly, partly as a function of the time and environment characterizing a person's early life. What were once considered privileges are now considered entitlements. This attitude change extends from the shop floor to the executive suite. There is increasing demand for a high quality of work-life, which in turn influences work-system design.
2. Major attention should be paid to chronic unemployment and underemployment. These developments may represent nearly irreversible catastrophic flips to new levels of equilibrium. Unemployment and underemployment are not simply levels or pools into and from which people flow mechanistically. Rather they represent the results of evolutionary processes whereby the individuals constituting the level and the level itself have changed qualitatively.

A paradox is created with regard to education and skill levels, which are difficult to assess and involve counterveiling forces. On the one hand, political and psychological pressures and grade inflation, coupled with mass education, appear to have reduced the quality of a given level of education. On the other hand, companies require higher educational and skill levels, aggravating the tendency to chronic unemployment of those with modest or obsolescent education and skill levels. At the same time there is a disparity between the educational and skill levels employers demand for many jobs and the abilities and skills actually required for these jobs. This disparity exacerbates the tendency to chronic underemployment. Work is a primary psychosocial need, not just a means of earning money and enabling consumption. Work provides meaning, dignity, a feeling of self-worth, and an opportunity for self-fulfillment. No work, poorly designed work, and exploitive work produce disaffection and alienation, which not only reduce the productive capacity of the sociotechnical work system but also spill over into the family, the community, and leisure-time activities. Workers displaced for economic and technological reasons are not necessarily easily transferred among industrial sectors, thus exacerbating chronic conditions. And chronic conditions breed hopelessness and decrease incentives.

3. The effects of automation and technical change may exceed a critical threshold. After assuming the role of a nonproblem following the 1966 release of the voluminous reports of the National Commission on Technology, Automation, and Economic Progress, automation and technological change may be poised to trigger a further catastrophic reconfiguration in the already weakened

employment/nonemployment system. Rapid advances in computer and communications technologies, and in the perceptualmotor and simple decisional aspects of artificial intelligence and applications to hierarchical industrial control and to industrial robotics, seem likely to have imminent effects on the nature and availability of work.

4. <u>The effects of disaffection and alienation are already profound</u>. The decade-long productivity slump is at least partly due to these factors. Alienated workers express their dissatisfaction on the job by increases in job turnover, absenteeism, foot-dragging, pilferage, vandalism, sabotage, crime, strikes, sick leave, alcohol and drug abuse, and psychosomatic reactions. In society at large, disaffection and alienation underlie the rapid increases in delinquency and crime, particularly random attacks and large-scale, attention-getting crimes like mass murder, assassination, arson, and skyjacking. The costs of delinquency and crime are huge, not only economically but also in terms of fear, societal breakdown, and the compensatory retaliatory measures taken.

5. <u>Production and productivity are complex and cannot be reduced to simple or uniform production functions</u>. The limitations apply not only to simple functions like Cobb-Douglas (used in the Mesarovic-Pestel and Bariloche world models) but to more elaborate ones as well. Production functions ignore, distort, or mask the effects of natural resources, technology, and labor. Perhaps their greatest limitation, however, is the assumption that if only enough and the right mix of capital and labor were applied to production, the results would be positive, increasing, and predictable. This assumption ignores the processes of saturation

and exhaustion. Historically, large increases in production and productivity were usually one-time-only occurrences, for example, the mechanization of agriculture, the switch from agriculture to manufacturing, the switch from industrial electromechanical control to electronic control, and the switch from physicians' house calls to physicians' seeing many patients at a central location. In many areas further improvements may be spurious or may displace additional large numbers of workers. Further, the decline in rate of growth of US productivity has often been attributed to declines in funding for R&D. But this explanation overlooks the insidious decline in creativity, rate and quality of discovery and innovation, and psychosocial climate in aging, ingrown funding and research organizations. In addition, there are many inter-industry and inter-organizational differences. For example, the "Japanese model" has already influenced thinking in many companies so that ideas like layoff rate are obsolete. Also, it is quite difficult to predice labor requirements for emerging jobs in the future world where the National Model will partially operate.

6. <u>Basing policies on ideas that arose in the 1950s and 1960s may yield dangerous outcomes</u>. Much economic theory seems hardly current. The Phillips curve tradeoff between inflation and unemployment provides a salient example. A given level or percentage of unemployment might be accepted by the constituents, given a particular configuration of the enveloping field of forces, until one small increment more results in surpassing a critical threshold of temporary stability and the system erupts in violence, looting, and arson. This is what is happening in English cities at the time of this writing. Prime Minister Margaret Thatcher's

monetarist tradeoff between inflation and unemployment, apparently unsuccessful on other grounds as well, seems to have been singularly poor policy.

In short: causal diagrams involving the factors just discussed could be quite different from those representing the National Model.

CONCLUDING REMARKS

The present author considers system dynamics to be an integral part, perhaps the core part, of a unified dynamic theory of the evolution of complex living systems. This paper has discussed theories and constructs that appear to extend or enrichen feedback-based system dynamics in building the larger theory. But how compatible are the theories and constructs when one approaches the tasks of actually constructing theories testable against the real world and models useful in policymaking?

Three categories of immediate further research are indicated:

1. Improvements of present policy-significant system dynamics models like the National Model to reflect better the behavioral/social and sociotechnical forces, findings, and factors.
2. Construction of models to interact with system dynamics models. System dynamics models could be variously entered, left, modified, and reentered. Probabilistic system dynamics was mentioned as an example of this approach. It was also suggested that a cascade of models might be designed involving alternating system dynamics and catastrophe theory or dissipative structure models. Considerable thought would have to be directed toward the situations that trigger exit from one model and entry into another. It would be relatively straightforward to "fudge" such situations.

However, model design should be based on a better understanding of the relevant realworld thresholds, fluctuations, discontinuities, etc.
3. Construction of a "unified field-theoretic" model which endogenizes all constructs. This task might yield major incompatibilities stemming from the basic mathematical model of system dynamics and the DYNAMO compiler. For example, full mathematical treatments of critical phenomena, catastrophe theory, and dissipative structures variously involve sets of nonlinear equations, partial differential equations, higher-order ordinary differential equations, and stochastic considerations. It might turn out that a simulation language like GASP IV would be more appropriate for this formidable task.

Continuation in the observation, collection, and interpretation of realworld phenomena and processes that can be used to test and substantiate the basic theory must of course at least keep pace with model-building and policymaking.

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