EQUILIBRIUM, CRITICAL POINTS, AND STRUCTUAL STABILITY AND CHANGE IN SYSTEM DYNAMICS AND SYSTEMS SCIENCE

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ABSTRACT

The need for grand unifying principles of the evolution of societal systems is stressed. Examples of such principles from other sciences are given. The economic long-wave or Kondratieff cycle is taken as a reference basis for the study fo the evolution of contemporary technological societies. A number of qualifications to the basic paradigm are made. Several areas of recent structural stability theory are discussed in terms of their relevance to societal evolution. Particular stress is placed on nonequilibrium and bifurcation situations. Structure-function-behavior interrelationships at and near critical points are considered the most important features pertinent to system change or reconfiguration. Attempts are made to provide a fuller integrated theory of societal evolution and structural change. A number of problems relative to system dynamics theory and modeling, and to the use of models in societal management, are introduced and suggestions for improvements made.

INTRODUCTION

This paper is a further attempt to develop an integrated field theory of societal structure and evolution, especially as pertaining to conditions around points of sudden reconfigurational change. The paper considers issues relevant to the design and use of large-scale computer simulation models in science and for policymaking. A number of emergent policy problems dealing with management *toward* the future society are discussed. Previous

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publications, including broader discussions and definitions and reference to earlier works of this and other authors, are [1], [2], [3], [4], [5].

That new approaches to theory modeling and management are vitally needed is evident from the mounting numbers and complexity of societal problems. Social, technological, and economic policies and institutions, that have apparently worked for decades, or longer are now widely perceived as faltering. One gets the the impression of the imminent collaspe of many policies and institutions, that have devleoped quite respectable lineages, followed by a major paradigmatic shift.

Both theoretical and realworld problems, of course, are those of the interrelationships among structure, funciton, and behavior and of evolution, stability and instability, and change in form. Recently, advances in theory, modeling and understanding of and data collection on realworld systems have greatly improved our capabilities for dealing with these complex systems on both theoretical and practical grounds. These advances include Forresterian system dynamics, new ways of looking at equilibrium situations, new approaches to describing discontinuous qualitative changes, and the availability of data on structural change in managed living systems, particularly ecosystems.

In the following subsection of this section we shall discuss further the reasons for our optimism about the immediate likelihood of developing an integrated theory of societal evolution. We shall also bring up the topic of "aging systems approaches," whose properties parallel those of aging technologies, organizational designs, management strategies, etc.

In the second section of this paper we shall review and evaluate research on societal long waves. In the third section we shall discuss different meanings of equilibrium and the role of equilibrium in structual stability and change. In the fourth section we shall discuss the existence and nature of critical points or thresholds beyond which system structure and behavior bifurcate or otherwise change qualitatively and quantitatively. In the last section we shall attempt a brief theoretical synthesis of societal evolution at our particular time in world history. We shall consider implications of the present structural instability for planning and policymaking for the management of society.

On Grand Unifying Principles

Recently there appears to have been a paradigmatic shift within science. Scientists in many fields are working on the same kinds of problems, namely, those adumbrated above as structure-function-behavior interrelationships, stability, change, and evolution. Increasingly, similarities rather than differences, are evident in apparently very different living and nonliving systems. Although the forces of institutional reaction remain strong, it appears that the decades - long pathological specialization no longer represents the unquestioned dominant voice of science. Theory- and model-building based on the search for suggestive analogies and metaphors and the use of general constructs (building blocks) can be called the constructural approach. Other, and I believe inherently doomed, attempts to overcome the artificial barriers set up by disciplinary specialization are the multidisciplinary (e.g., how do you get sociologists and engineers to work together in urban design?) and interdisciplinary (e.g., what are the interfaces or interrelationships between economics and sociology?) approaches.

The integration of previously separate bodies and knowledge has been spectacular in several sciences, perhaps most so in molecular biology, geology, and theoretical physics. I shall comment briefly only on the last two.

In geology the grand unifying principle is plate tectonics. Plate tectonics, which was fully formalized in the early 1970s, integrated major geological concepts that went back more than a century. Each concept in turn was underlain by substantive subconcepts and by verifying evidence. The major concepts include continental drift, building of major mountain chains, origin and distribution of volcanos, origin and distribution of deep ocean trenches, distribution of mid-ocean ridges, origin and distribution of earthquakes, shifts in paleomagnetism, and the behavior of large strike-slip faults like the San Andreas.

Grand unifying principles apply at two levels in theoretical physics. Since Einstein, attempts have been made to develop a unified field theory of gravitational, and electromagnetic, weak nuclear (e.g., in radioactivity), and strong nuclear (e.g., in quark bonding of protons) forces. A quantum field theory at the elementary-particle level now unifies the last three kinds of interactions [6].

At the atomic and molecular levels scientists have long been familar with phase shifts, rather dramatic shifts in structure and behavior on either side of a critical point, typically a critical temperature. Superficially very different substances, for example, gas-liquid mixtures, immiscible-liquid mixtures, ferromagnets, metal alloys, and solid-state devices display very similar behaviors. These behaviors are called critical phenomena. The similarity of qualitative behavior was recognized by Landau in the 1930s and is called mean-field theory. Mean-field theory explained mean or average behavior, but neglected fluctuations. Recent theory explains how quite dissimilar appearing substances show quantitatively exact behavior (i.e., have exactly the same critical exponents) in the neighborhood of critical points. Identical behavior is dependent on having the same dimensions of space and of order parameter (a macroscopic or emergent property such as susceptibility to magnetization).

The existence of critical points or regions "near" these points and of incipiently changing structure and behavior is a key construct in the theory I am attempting to develop.

I feel far less optimistic about the progress, both theoretical and applied, made in the last two decades in any of the traditional behaviorial, social, organizational, and management sciences. In spite of "exponential" growth in the numbers of practitioners, publications, university departments, students, and so on, one gets the impression of stagnation in theory-building, basic research, and applications. Such fields as human factors, operations research, systems analysis, systems management, public administration, and systems engineering may have passed their useful performance peaks and may have little more to offer in terms of needed radically new ideas. Many systems dynamicists would add econometic modeling to this list! This problem of the aging of institutions and practices and of structural bonds is pursued in greater detail throughout this paper.

One major attempt to develop a grand unifying principle for social systems — an approach that can powerfully challenge the intellect and inspire the efforts of others — is that of Jay W. Forrester. With system dynamics, and especially with the recent work on the System Dynamics National Model of the socio-economic system of the U.S. and other developed countries, insights have emerged that help explain short- and long-range cyclic behavior and reconcile once apparently contradictory economic behaviors. These holistic patterns of behavior include, as relevant to today, simulataneous low productivity, aging institutions, stagnant economic growth, differential industrial performance, high unemployment, industrial overcapacity, high interest rates, recession, inflation, and (I add) increased speculatory behavior. See, for example, [7, 8].

There has been some confusion over the meaning of the term system dynamics. It can mean the specific theoretical and

modeling approach developed by Forrester. It also has a more generic meaning referring to the behavior of any dynamic(al) system. Partly for this reason, and partly to coincide with systems analysis, systems engineering, systems science, etc., I have long urged the use of systems dynamics to describe Forrester's approach. A number of different kinds of "system dynamicists", including dissipative-structure theorists, met at the 7th International Conference on System Dynamics held in June 1982 in Brussels. At that time the term classical system dynamics arose as a description of Forrester's approach. Perhaps Forresterian system dynamics might also be appropriate. At any rate, the conference represented one step further toward the development of a grand unifying principle for the societal sciences. See [9] for further discussion of the conference.

SOCIETAL LONG WAVES

A major deficiency of science, outside cosmology, geology, palentology, and evolutionary biology, has been its emphasis on cross-sectional ahistorical theories and methods. Even subjects like history have been fragmented, with overemphasis on great persons and specific events, and with associated nelect of basic driving forces and dynamic behaviors. Recently, many economists, stimulated largely by today's recurrent crisis and deteriorating economic situation, have begun to take a much longer-range view of the processes of economic change. The partially forgotten work of men like J. van Gelderen, N.K. Kondratieff, J.A. Strumpeter, and J. Schmookler have been revived, reexamined, and reinterpreted.

Economists and many modern businesspeople speak increasingly of economic long waves and Kondratieff cycles, and concern over the causal factors underlying and means of controlling these patterns has become an active area of research. For example, the entire August 1981 issue and most of the October 1981 issue of Futures was devoted to this topic.

Before analyzing and interpreting some of the crucial points made by other authors, let us first see how the concept of economic long waves fits into the theory of societal evolution that I am trying to develop. Earlier presentations of this theory, that emphasizes families of logistic (or logistic-like or convex-up parabolic) curves of social/cultural, demographic, and technological change, with these curves sometimes overlapping and sometimes separated by discontinuities and overall bounded by a hyperbolic envelope curve, are given in [3] and [4].

Fundamentally, I question the existence of "economic" long waves, in the sense that the economic factors are the sole or main contributory, causal, or controllable factors. I question that cycles or recurrent patterns of rise and fall or growth and decline are inherent only in the structure of Capitalism or of the industrialized world since the beginning of the Industrial Revolution. Rather, I propose that such recurrent patterns are intrinsic features of human organic and cultural evolution. The primary concept is that of the sociotechnical system, which also typically has economic and political dimensions. Indeed, the primary role of technological change is stressed by many of the Futures authors, and others emphasize the need for associated social or institutional innovations (e.g., Forrester [7], [8]).

There is much evidence for alternating continuity and discontinuity in human evolution. Carneiro, for example, (cited and discussed in [3] and [5]) contrasts periods of development (i.e., discovery, invention, and innovation) with periods of growth (diffusion of established technologies and practices). In Anglo-Saxon England the period of development lasted between 450 and 650 A.D. where it was separated by a discontinuity (change in slope) from a period of growth that lasted until 1087 A.D. The second period represented a consolidation and spread of basic innovations from the first period.

Many analysts identify four long waves since the beginning of the Industrial Revolution with troughs and peaks for each wave given as follows: (1) late 1780s/about 1816; (2) 1843/about 1863; (3) 1896/early 1920s; and (4) late 1930s/late 1960s. A fifth trough is often predicted to occur near the year 2000. Successive waves have been associated with different dominant technologies and nations. The first wave involved mostly Britain and the technologies of textiles and steam power. The second wave involved more of western Europe and drew heavily on coal, the railways and mechanization of production. The third wave involved also the U.S. and exploited electrical power, the petroleum industry, the chemical industry, and the internal combustion engine. The present wave, increasingly worldwide, has been closely associated with electronics and computers, ariplanes, and further advances in the chemical industry such as plastics, pharmaceuticals, and synthetic fibers.

In placing these long waves in the broader context of long-term evolution, Piatier [10] uses the concept of *an* industrial revolution. He includes the Neolithic revolution based on agriculture, animal husbandry, and settled village life with its spinoff of greater hierarchical or bureaucratic organization and master and slave relationships.

But why limit concern to such isolated revolutions? Why not provide a sequence of sociotechnical and social revolutions, each of which might be regarded as a bifurcation point in human evolution? A detailed presentation of the argument is beyond the scope of this paper. However, a full understanding of societal evolution, *and an understanding of forces operating near the present and in the future*, would also have to include these representative revolutions: (1) the pre-Paleolithic recognition of the importance of tools and the passing on of the knowledge from one generation to the next; (2) the pre-Paleolithic or Paleolithic discovery of the controlled use of fire; (3) the successive Paleolithic refinements in the knapping of flint and other raw materials used for tools (these successive technologies were, by the way, one of the bases for the development of hyperbolic-growth theory), (4) the Mesolithic or Neolithic discoveries of agriculture and the domestication of animals and the spinoffs mentioned above; (5) the late Neolithic invention of the wheel; (6) the discovery of the use of copper, tin, zinc, and iron for weapons and other

implements; and (7) religious changes, perhaps most importantly the Protestant Reformation, that led to an excessive drive to excel, to the familiar "work ethic," and to rapid expansion of knowledge and trade in some countries while other countries remained static.

Quite obviously the history just adumbrated shows a telescoping of sociotechnical change. Stages, defined in terms of the span from first discovery of a new idea or technology through complete satuation of the cultural environment with the resulting and diffused innovation, may have lasted hundreds of thousands of years in the early Paleolithic, several hundreds of years in the early Middle Ages, and several tens of years recently. Probably from the very beginning the sociotechnical system consisted of a complex of interrelated ideas, beliefs, technologies, and practices. Such complexes are much larger and have much faster and greater impacts on the environment today. Recognizing these complexities and their impacts —that is, recognizing the *total field of forces* — should caution us against any monocausal explanations of societal long waves and against any precipitous implementation of policies. Consider in [11]: " ....proposal may provide an alternative to Reagonomics."

Another observation important to the building of the unified theory and to systems science is the ubiquity of wave forms or cycles. They appear to characterize most living and nonliving systems. Examples include the Big Bang expansion (and contraction?) of the Universe, the birth and death of galaxies and stars, glacial epochs on Earth, seasons, oscillating chemical reactions, circadian rhythms, estrus and menstrual cycles, and manic-depressive cycles. Thus, one should be surprised if various cycles or waves did not exist in the socioeconomic macrosystem, not that they do. Further, these cycles are usually complex and may differ qualitatively on either side to a bifurcation point. For example, the Pleistocene glaciation was characterized by at least four advances of the ice separated by at least three interglacial periods. Each gliacal period was punctuated by at least one interstadial or warmer period, and each interglacial period by at least one "litle ice age." A recent report on the origin of the Pleistocene glaciations [12] shows the influence of exogenous and endogenous forces, the amplification of the results in changes in Earth's axis of rotation, precession of the equinoxes, and eccentricity of orbit, and the reverberation of changes throughout the climatic system. With minor changes in insolation, the ice-covered area slowly increased until, castastrophically, the ice tripled in area and an ice age occurred. Iceberg calving in lakes below the glaciers led eventually to catasphopic retreat of the ice. Both the mechanisms of system dyncmics and of catastrophe theory are involved in these realworld phenomena. I believe such a model also is typical of sociotechnical and economic systems.

Futher, if we consider suddenly falling asleep and sudden awakening as behaviors following bifurcation points, the electroencephalographic wave forms are quite different in the waking state from the sleep state. In ecosystems different type waves form (even chaos) may follow critical bifurcation points.

In many analyses of economic long waves, emphasis is placed on actions such as maximizing profits. A fuller analysis of human behavior, for example, the task analysis used in human factors and industrial engineering, penetrates also into the decisions and information that antecede actions. We should also note Herbert Simon's analysis of the classical model of the firm and his replacement of optimizing behavior with satisfying behavior. It may well be that profit maximization and other simplification are far from being the major driving forces underlying economic long waves.

In all Communist and socialist countries today, there is evidence of social malaise and economic, technological, and ecological failures. Consider the bankruptcy of Poland and Romania, the near revolution in Poland, the chronic shortages of at least some kinds of food in almost all Communist countries, and the failures in the production of consumer goods in most of the countries. It is highly unlikely the economic long waves stem solely from the inherent deficiencies of Capitalism. There may, however, be families of long waves, differing from researcher to researcher as dependent on the particular monetary, industrial, or technological emphasis. As theory-builders and modelers, we must be quite certain that we are dealing with the whole sociotechnical system and not just with selected abstractions as is highly likely in the absence of a complete historical record. In some cases model reproduction of historical patterns may be merely coincidental or even tautological.

The range of long-wave periods from 40 to 60 years can produce an error of up to 50 percent. This is still a way too imprecise, and much more must be discovered about the dynamics that generate such variability. Alternatively, different forces may operate to produce waves of different duration. If stark non-equilibrium conditions, bifurcations, catastrophes, and dissipative structures, as well as equilibrium-seeking, smooth feedback loops, do play a role in this form of societal evolution, as I emphasize, then we should attempt to identify the critical bifurcation points. Examination of a sequence of idealized Kondratieff waves (see [4] and [11]) suggest for each wave the sequence: (1) a trough; (2) a less steep followed by a steeper rise to a peak; (3) a steep decline from the peak (primary recession following a war) followed by a minor recovery; and a steep followed by a less steep plunge to a trough. Let us assume, for want of a better starting point, that trough, primary peak, and secondary peak following the brief recovery are critical bifurcation points. Around these points one would expect the greatest system instability. The critical points could be considered, in catastrophe theory terms, to be associated with unstable equilibrium manifolds. The oscillations around the peak especially suggest conflict between the forces of the old way and those of the new, which finally prevail. In the simulations of the System Dynamics National Model, the steep plunges from peak to trough also suggest more discontinuity than continuity (cf. Figure 2b in [13]).

In brief summary: the purpose of this rather wide-ranging discussion has been to caution against both single-cause explanation and solely local-cause explanations of societal long waves. I propose that the basic underlying driving forces in the present evolution of world society are those fo the life history of human collective behavior. Human ideas, tools, institutions, and practices are born, grow, are accepted and developed further, and diffuse throughout the society, but finally environmental or inherent structural limits or new and more competitive ideas, etc., appear, which hasten loss of adaptive fit and the decline or extinction of the old. Much of the theory has, of course, been proposed by other authors, and the concept of societal stagnation and aging appears to be firmly embedded in Forrester's theory behind the Systems Dynamics National Model. Thus, my theory appears to be broad enough to encompass the areas of concern expressed in the August and October issues of Futures and in the system dynamics literature, while at the same time being capable of incorporating the new constructs of structural stability. We shall examine these constructs and their application to the theory of societal evolution, particularly to the present stage of world transformation throughout the rest of the paper.

EQUILIBRIUM, NONEQUILIBRIUM, AND STRUCTURAL STABILITY

It is probably fair to say that equilibrium theory has dominated most of science until very recently. And the concept of a perturbable equilibrium is closely related to that of systems stability. Prominent examples include servomechanisms, cybernetic regulation and control of manned and unmanned vehicles, homeostasis in physiology, and, of course, the "law" of supply and demand in economics. Such systems include the large class of self-regulating systems, which may have very narrow tolerance for deviation from a criterion level. Perturbations that are so servere as to force the system so far from equilibrium that the regulatory negative-feedback links are broken usually result in the destruction of the system (the airplane crashed in turbulent weather, the patient died from inability to regulate electrolyte balance, the stock market crashed). Systems of competitive or conflicting subsystems, such as ecosystems and international systems, also can show equilibrium behavior and experience the effects of perturbations that destroy the system and render one or all populations extinct. This kind of situation is one of several important to maintaining international stability in the sense of avoiding war [2], [4], [5].

It is said that equilibrium, a situation in which the system levels do not change over time and the rates are zero, is central to system dynamics. Certainly, elementary textbooks such as Goodman's [14] and broad integrative overviews such as Toward Global Equilibrium [15] appear to bear out the emphasis. The part of the logistic curve past the inflection point in the "life cycle of economic development" (life cycle of a [stage of] a civilization) is also considered to be moving toward equilibrium.

But recent systems theory indicates the possibility of several kinds of equilibrium situations. System dynamics deals with the stable and unstable equilibria and with disequilibria and unrestrained growth and attempts to restore equilibrium, but apparently not explicitly with simultaneous multiple equilibria and flips among them as in catastrophe theory or with greatly displaced nonequilibrium states as in dissipative-structure theory. These more complex equilibrium configurations can be the basis of irreversible movements to qualitatively different system behaviors and even for structural change. Thus, we can contrast the self-regulation of structually unchanging systems under perturbed equilibrium conditions as discussed above with the self-organization of systems driven far from equilibrium (nonequilibrium situations) and then perturbed exogenously or made more susceptible to endogenous fluctuations.

The need to distinguish among these different equilibrium situations is not a trivial matter. For example, Mensch, et al. [16] write of a non-equilibrium theory but appear to be referring to an economy's proceeding from one disequilibrium state to another. To me a disequilibrium (out of equilibrium) state potentially can return to equilibrium, whereas a nonequilibrium (equilibrium no longer exists or is possible) state can lead to increasing internal and external fluctuations, to bifurcations, and to structural change. Further, although Mensch, et al. hint in the direction of dissipate-structure theory without explicitly mentioning it or its authors, their concepts of structural stability and structural change still appear to be undeveloped in the framework of modern structural stability theory.

"Stability" thus also has different meanings. Roughly, it is the capability of a system to respond to perturbations, fluctuations, and random disturbances while still maintaining about the same dynamic behavior over some period of time. Stability is often further expressed as local or neighborhood, global, or neutral stability. Recently, stability has been contrasted, particularly by ecologists, with *resilience*, the ability to absorb relatively strong perturbations without system breakdown. In the simplest deterministic condition (local) stability refers to the tendency to return to an equilibrium point. *Lyapunov stability* refers to the maintenance close to equilibrium of the future time-trajectory of a system slightly perturbed at the origin from equilibrium. *Asymptotic stability* refers to the propensity of the system eventually to return to the equilibrium point. Globally, many system dynamics models appear to display this kind of stability behavior.

Classical stability may be contrasted with *structural stability* [17]. In the former the effects of external perturbations acting on a fixed system such as a classical pendulum are stressed. Changes are in the external environment, and the system itself does not change. Search is for the system's equilibrium points and the associated dynamic behavior near these points. This approach would appear to have little relevance to societal systems and ecosystems functioning far from equilibrium.

The concept of structural stability emphasizes qualitative changes in the trajectories of the system when the system structure is perturbed. System behavior is examined with respect to that of all "nearby" systems. If the behaviors are the same, the system can be said to be structurally stable. A sufficiently small perturbation to the dynamics of a structurally stable system will yield an equivalently small change in dynamic behavior.

Single or families of differential or difference equations can be used to model biological and social systems. The effects of external perturbations and noise and internal fluctuations on the stability of the solutions to the equations and presumably on the structural stability of the realworld analogs can then be tested. These methods reveal many interesting and unexpected results, some of which we shall return to later in this paper.

Equilibrium still must be recognized as a powerful *attractor* state in systems evolution and behavior. But complex systems appear frequently to show successive instabilities as the system proceeds farther and farther from equilibrium. These systems can be studied by various kinds of bifurcation theory, of which catastrophe theory is one specific example. Prigogine [18, p. 105] states that "in principle, a bifurcation is simply the appearance of a new solution of the equations for some critical value." Typically, there are successive bifurcations from the "thermodynamic branch" or equilibrium state, either branch of which may produce stable or unstable solutions. The thermodynamic branch describes the solution to nonlinear equations that correspond to thermodynamic equilibrium and that can be continued into the nonequilibrium range. Significantly, this thermodynamic branch can become unstable at some critical distance from equilibrium, presenting numerous successive primary and secondary bifurcation points. Such systems involve both deterministic and stochastic processes. Between the bifurcation points, the system appears to obey deterministic laws. But near the critical points fluctuations exert an increasingly important influence that determine the branch that the system evolution will follow.

Unfortunately, recent work on chaotic behavior to which we shall return below, blurs the distinction between determinism and stochasticity. Nevertheless, it may be that classical system dynamics is most applicable to smooth periods of growth and decline [1], [4]. System dynamics may be much less applicable around critical points and discontinuities and reconfigurations of the field of forces in societal systems evolution. As some authors in the August and October issues of Futures question, economic long waves may not really be wave forms but just such successive restructurings as I propose.

CRITICAL POINTS, LINKAGES, AND SYSTEM RECONFIGURATIONS

I believe that search for critical points and neighborhoods and behaviors characteristic of these domains is now the critical (!) problem in the study of societal, indeed all, evolution. The problem can perhaps first be summarized by considering critical phenomena in physics. Critical phenomena characterize phase transitions such as the liquid/gas metallic alloy, immiscible/miscible liquid, and paramagnetic/ferromagnetic. Superficially different substances obey the same qualitative and quantitative laws. We shall restrict our attention to the behavior of (models of) magnets, especially as summarized in [19].

The salient features about magnetism that might be generalizable to societal systems are these, First, behaviorally the ferromagnet has a clearly identifiable critical point, the Curie temperature at 1044 degrees K. Well above the Curie temperature iron displays no spontaneous magnetization. As the iron is cooled th the neighborhood of the Curie temperature, there is still no magnetization. At the Curie temperature magnetization abruptly occurs, and below the Curie point magnitization increases smoothly. Second, structurally, well above the Curie temperature little order exists, that is, the microscopic system constituents, the magnetic moments of single atoms, are randomly distributed. At lowest temperatures, longer-range order, correlation among atoms with the same electron spins, has emerged. At the Curie temperature these patches of macroscopic order exoand to infinite size and magnetization suddenly, spontaneously occurs, but fluctuations of all scales remain. Third, external fields of forces can exert major effects on structure and behavior.

Magnetic susceptibility, the change in magnetization induced by a small applied field has relatively little effect at high temperatures (the iron cannot retain any magnetization) and low temperature (the iron is already magnetized and cannot change much more). But in the neighborhood of the Curie point, either a small change in temperature or in the external field can give (catastrophically) a large change in magnetic state. Near the Curie point, the susceptibility rises "exponentially": at the critical temperature itself, the susceptibility becomes infinite.

Fourth, the macroscopic peoperties - for example, correlation length, spontaneous magnetization, and magnetic susceptibility —of such thermodynamic systems are functions of the distance of the system temperature from the critical temperature. Further discussion of the nature of reduced temperature and critical exponents is beyond the scope of this paper.

Sixth, a coupling strength, K, involving nearest-neighbor interactions can be defined as the reciprocal of the temperature. This coupling strength can be changed with a renormalization-group transformation (successive averaging out of fluctuations) by which the distance between neighbors increases or decreases. Only when K continues to equal one, does the critical fixed point on an imaginary multidimensional surface in parameter space coincide with an unstable equilibrium. Other values of K may diverge either toward zero or toward infinity. As in catastrophe theory and bifurcation theory, and rather counter to system dynamics theory, systems do appear to be quite sensitive to differences in initial conditions.

Clearly, in viewing societal evolution, critical bifurcation points, can be identified. Beyond these points, some state of the world is irreversibly changed forever. The easiest points to identify are military and political, but some economic and technological points can also be recognized. On December 20, 1860 South Carolina seceded from the Union; on December 17, 1903 the Wright Brothers made their first controlled and sustained flight at Kitty Hawk, North Carolina, on Black Friday, October 29, 1929, the Wall Street stock market crashed; on September 1, 1939 Aldolf Hitler invaded Poland. Sometimes such events can be pinpointed to the exact hour and minute.

It seems to be equally clear that in the neighborhood of critical points, fluctuations in form and scale increase and that the susceptibility to system reconfiguration increases greatly. Unfortunately, most of our knowledge about such behaviors is derived in retrospect. Rumors of war and increasingly belligerent acts and provocations preceded both the U.S. Civil War and World War II, as well as almost all other wars. Active trading by the New York Stock Exchange was several times the normal volume in the months just before the crash. In our present downturn of the latest societal long wave, fluctuations in life styles, music, judicial interpretations, employment, inflation, interest rates, and business and government practices have been striking. Forrester [8] writes of the increasing amplitude of business cycles. One gets the impression today of a changing collective consciousness (an order parameter in the sense of pbysical critical phenomena) and of a field of forces incipiently preconfigured. Linkages are weakening among elements and subsystems, but people, at least subconsciously aware of imminent changes, are desperately trying to restore some order and some amount of control over the eroding old system. The world system-field is now in a critically metastable state when even slight perturbations or fluctuations can drive it into a radically different configuration.

A reconfigurating field fo forces can be characterized in a number of ways (see [3], [4], [5] and references therein). Here we shall be concerned mainly with the formation and weakening of linkages among elements, changes in system-environment boundary interrelationships, and forces that push the system farther and farther into the nonequilibrium region of structural instability.

The system can arbitrarily be considered to span one or more of the logistic-curve growth stages in the theory of socio-technical evolution mentioned earlier. Early in the evolution of the given system, there may be some partially viable fragments of the old system and environment. More importantly, the field is still susceptible (the climate of collective consciousness is conducive) to the acceptance and nucleation of social, technological, and (formerly in human evolution) biological mutations. Like some of the authors in the August and October issues of <u>Futures</u>, I believe that such mutations are clustered in space and time. Ecological, geographical, and historical reasons for clustering could be given, but would unduly extend the length of this article.

Note that this approach is somewhat different from that of Nicolis and Prigogine [20] whose structural fluctuations, at least in termite nest-building and army-ant swarming, are randomly distributed.

Nucleations form as a function of both proximity and attractiveness. The old system-environment boundary interrelationships have broken down in the domain on either side of the critical point, and the environment can no longer damp the growing force of the nucleations. These nucleations may abruptly spread to engulf the entire system. Eventually, strong bonds are forged among elements and subsystems of the new system , fostering growth and stability. Some features of the field of forces may be permanent, for example, attractors that draw the system toward equilibrium. However, linkages ultimately age and weaken. It is known from physiology and psychology that repeated stimulation can lead to saturation of effect, failure to reinforce, and functional shifts. It is likely that this is a primary reason for the aging and breakdown of system linkages, and, in the macrosystemic sense, for the aging and breakdown of industries and institutions. The system has aged, become structurally unstable, and is ready for the next reconfiguration.

From my perspective one of the serious limitations of system dynamics modeling is the persistence and constant strength of the linkages in positive and negative feedback loops, which should wax and wane and perhaps, eventually disappear.

May [21], in discussing the relationships between system stability and system complexity, summarizes work on linkages or and ages through one of the stages mentioned earlier, the stability - enhancing semi-autonomous subsystems are lost and that an increasing homogenization occurs, and that the interconnections and the strength of interactions within the larger system and between the system and its natural environment increase. With equilibrium configurations limited to restricted ranges of interaction and environmental parameters (not constants!), with increasing severity of perturbations and fluctuations, and with a probable rigidification of present system linkages, it would appear once again that world society is fast approaching a critical threshold for reconfiguration.

It appears that stability is a much more complex phenomenon than was envisioned until recently. In brief: complex systems can evolve progressively or be driven from regions of narrower and narrowerer equilibrium-seeking stability to regions of increasing fluctuations, multiple equilibrium and new organization, to regions of strangely patterned fluctuation, turbulance, or chaos and system collapse. Day [22] has reviewed the history of the concept of chaos and brought it to the attention of system dynamics audiences. In chaos even simple deterministic nonlinear difference or differential equations, iterate to depict changes over time in physical, biological, and behavioral/social systems, can endogenously generate behaviors that resemble exogenously imposed random stochastic processes. This finding certainly provides further ground for debating the "exogeny-endogeny problem" in system dynamics.

interconnectively and stability. For example, studies of models of randomly assembled food webs can be expressed in terms of three parameters: S, the number of species; C, the average connectance of the web; and b, the average absolute magnitude of the interaction between linked species. Considering the interaction coefficients ("self-regulatory terms") to be $b_{ij} = -1$, for large S the systems will be stable if: $b\ (SC)^{\frac{1}{2}} < 1$

Otherwise they will be unstable, that is, increasing complexity defined by an increasing number of species, or increasing connectance, or increasing interaction strength can decrease dynamic stability. That is, increasing complexity in these models yields a dynamic <u>fragility</u> rather than robustness. May defines dynamic fragility of a system to be stability only witnin a comparatively small domain of parameter space. In unpredicable environments, such as the societal environment of today, the stable region of parameter space would have to be extensive, implying that the system must be relatively simple.

Empirical tests have been made of the constancy of the product, SC, as species richness varies [21]. The product has been shown to be constant, with the underlying mechanism's being the tendency for larger systems to be organized into small subsystems of species, with most interactions taking place <u>within</u> these subsystems. Thus for given S and C, dynamic stability may be improved by assembling the food web as a set of loosely coupled subunits. May's conclusions are strikingly similar to those of Ashby on loosely connected subsystems and of Simon on the architecture of complexity. It appears that, as human society evolves

Of more concern in this paper, however, is the great variety of forms systems evolution can take, especially as bifurcations occur more frequently. A review of conditions contributing to alternate system states has been made by May [23].

Surprisingly complex behaviors can be generated through iterations of the simplest difference equation:

$$X_{t+1} = F(X_t)$$

Consider the specific example of the nonlinear function F(X), the "logistic difference equation":

$$N_{t+1} = N_t \ (a - b \ N_t)$$

This and similar equations contain one or more parameters which "tune" the steepness of the hump of the curve. For $b = 0$ and $a > 1$, the population grows exponentially. For $b \neq 0$, the quadratic nonlinearity yields a growth curve the steepness of which is tuned by the parameter, a. Disregarding some simple mathematical transformations and restrictions on the allowable non-trivial interval of a, equilibrium values (fixed points) and their stability can be investigated. For a single-hump curve there is one non-trival equilibrium solution to X. The stability of the equilibrium point, X*, depends on the slope of the F(X) curve at X*. At first, say, at slopes between 45° and -45°, the equilibrium point is at least locally stable, attracting all trajectories in the neighborhood. But as the parameter is tuned so that the curve F(X) becomes even more steeply humped, the equilibrium points becomes unstable. Successive iterations increase the likeihood of instability. At exactly this new unstable point, there occur (for Iteration 2) two new and initially stable equilibrium points of period 2 between which the system alternates in a stable cycle with period 2. The single-hump curve now has changed to a two-hump form. Beyond a critical steepness the period 2 points also become unstable and bifurcate to give an initially stable cycle of period 4, which in turn yields to a cycle of period 8, and then to a hirerachy of bifurcating stable cycles with periods 2^n, that is 16, 32, 64..... May believes that this process is generic to most functions F(X) with a steepness of hump that can be tuned.

The range of parameter values that define the stability of any one cycle progressively diminishes and is bounded above by some critical parameter value, a point of accumulation of period 2^n cycles. This value can usually be calculated exactly. Beyond this critical point, for example, for $a > ac$, there is an infinite number of equilibrium points with different periodicities and an infinite number of different periodic cycles. Further, there is an infinite number of initial points, X_o, which yield totally aperiodic trajectories. No matter how many iterations, the pattern is never repeated. This picture of an infinite number of different orbits is the "chaos" referred to above. As defined by increasing values of a, the fixed point becomes unstable before the chaotic region beings. Also, there are stable cycles even within the chaotic region. This situation is suggestive of the critical phenomena in physics discussed above.

Similarly, the relationship between X_{t+3} (the ordinate) and X_t (the abscissa) can be obtained by three iterations of the above equation. The hills and valleys become more pronounced as the parameter a increases, and six new period-3 points (points of intersection with the 45° line) appear. This can be plotted as two cycles, each of period 3.

May distinguishes between two different kinds of bifurcation processes for such first-order difference equations. First is tangent bifurcation, as summarized just abore, in which the hills and valleys of higher iterations move, respectively, up and down to meet the 45° line. At the moment these hills and valleys become tangent to the 45° line, a pair of new cycles of period k, one stable and one unstable, arises. Pitchfork bifurcation arises when an originally stable cycle of perion k may become unstable as F(X) steepens. The slope of the given iteration at the period k points steepens beyond -1, where a new and initially stable cycle of period 2^k appears.

There are two critical parameter values: (1) that in the chaotic region in which the first odd-period cycle appears, and (2) the point at which the period-3 cycle first appears ("period three implies chaos").

Most importantly, these seemingly erratic flucuations may stem from a rigidly deterministic population-growth relationship. For our purposes, "population" is not limited to numbers of living organisms, but may apply also to ideas, innovations, strategies, practices, sociotechnical units, and so forth. Further, in the chaotic region, arbitrarily close initial conditions may produce trajectories that eventually diverge widely. Another, perhaps related

kind of divergence is seen in catastrophe theory when initially close behaviors diverge on either side of the manifold. Long-term prediction thus becomes impossible.

In studies of fluid turbulence, as a certain parameter is tuned to a set of deterministic equations, motion can display an abrupt transition from a stable configuration such as laminar flow into a chaotic regime [23], [24]. I believe that it is of paramount importance to search for such critical points in the turbulent-environmental field of societal science. In evolving societal systems also an appropriate model might involve the sequence: monotonic damping, damped oscillations, stable limit-cycles, and chaos associated with system collapse and reconfiguration. In higher-order or higher-dimensional systems, chaotic behaviors may occur under even less severe constraints (e.g., less severe nonlinearities or less steeply humped F(X)) than is the case with the one-dimensional systems summarized above.

As with models, however, the question of fidelity arises here too. For example, to what extent is the erratic behavior an artifact of numerical analysis or computer simulation? A number of realworld physical systems ranging from simple electrical circuits to complex fluids do show the transition to chaos in quantitative agreement with the theoretical predictions. There appears to be a remarkable correspondence with the second-order phase transitions in magnetism which we discussed earlier under the topic of critical phenomena. Once again there appear to be universal numbers for superficially very different systems [24].

And, very importantly, once again we see a movement toward grand unifying principles. The onset of trubulence also can be thought of as a kind of phase transition. It may be described by a succession of three transitions at most (as above, "period three implies chaos"). Thus, the transitions to choas themselves may be orderly and predictable, at least in physical systems.

To conclude, we note that the recent advances discussed in this section touch on several fundamental assumptions of system dynamics theory and modeling methodology. These are the insensitivity, with respect to qualitative behavior, of the system/model to changes in initial conditions and parameter values. Using more conventional techniques of sensitivity analysis, Vermeulen and De Jongh [25] also report that qualitatively diffent behaviors can result from even small perturbations of the system. It may be that some of the basic theoretical assumptions of system dynamics should now be reexamined in the light of new knowledge.

EVOLUTIONARY DYNAMICS AND THE MANAGEMENT OF SOCIETY

A mental synthesis of the many ideas presented in this paper, and attention to the turbulence in the real world, indicate an urgency in developing better understanding of the dynamic processes of societal evolution, our capabilities for building theory about and modeling these processes, and the role of our models in the management of complex systems.

We have taken, as a major mode of reference for societal evolution during our times, the concept of a series of economic

long-waves or Kondratieff cycles. But perhaps, although major changes in society are undeniable, the concept of continuous waves in spurious. I believe that a more likely situation is succesive configurations (structures) of the world societal-field separated by briefer periods of stark reconfiguration (structural change) that asymetrically surround critical points of bifurcation, discontinuity, catastrophe, and emergence of qualitatively new order. Each configuration eventually ages and wears out becoming ever more vunerable to exogenous perturbations and endogenous fluctuations. Of course, any system as complex as modern industrial society has enough "variables" to present a picture of continuity even though the major qualitative dynamics are fundamentally discontinuous.

Whether the concept of continuous waves is the most realistic way of describing societal evolution or not, the patterns of interacting primary industrial (capital sector), secondary industrial (consumer - goods sector), employment, economic, strategic, human behavioral, and other factors, verbally described by Forrester in [7] and [8], provide a powerful basis for further theory- and modeling building. But there does appear to be a disparity between these verbal descriptions and the present output of the System Dynamics National Model. Forrester's theory or conceptual model appears to be way ahead of the assembled computer simulation model. Many of Forrester's statement fit in nicely with what I call "field theory", but I am not certain how well these ideas can be translated into model structure. One example is the coupling mechanisms underlying entrainment [7, pp. 538-539]. In fact, here is one of the best examples of what is meant by a field of forces. Forrester writes:"..it is reported that several pendulum clocks in the same room can begin to swing in unison because of a slight coupling through the structure of the room." In the entrainment of national economics, perhaps the concept of an "attractor" -- a state that attracts all neighboring trajectories -- would also be of value. Nevertheless, greater specifications of the entraining force appears necessary.

Further [7, p. 540], Forrester writes, concerning the upswing of a long wave: "There is a high degree of unity and interrelatedness to all that must happen. ....about half way, the style and pattern become rigid. ....A radical improvement does not fit...." The integrating field of forces may well involve collective intelligence, collective perception, and collective cognitive exhaustion. And [8, p. 8], Forrester writes: "The long wave is accentuated by the length of people's memories of past economic disasters,...." Can these emergent field-theoretic concepts be explicitly incorporated into the model structure, or must they be implied as part of the educational and managerial processes?

Further, Forrester [7, p. 541] states: "Research must focus more sharply on the bridge between micro-structures and macro-behavior." This, again, ties in with my field theory of emergent pheromena.

Not only may past long waves actually represent mentally synthesized segments separted by discontinuties, but the outcome of the present downswing may be radically different from past recoveries. Indeed, there may be no recovery, but rather one of history's major reconfigurations. This could occur because of the superposition of several fields of forces. Forrester [7] proposes a simultaneous occurrence of the long-wave peak and the transition region (region near the inflection point of a logistic curve) of the life cycle of economic development (life of a civilization or major segment of a civilization). He writes: "...our social and economic system will be buffeted by a combination of forces that has not previously been experienced" (emphasis added). To these fields, I add the nonequilibrium structural-stability changes characterizing the field of forces emphasized in this paper.

Moreover, even if another recovery were to occur, we might expect it to be qualitatively much different from previous ones. A major structural change in employment is most likely, a change characterized by massive social disruption. It is likely that the major industries of such a recovery would be based on innovations in robotics, factory automation and biotechnology [26]. These industries, and their spinoffs and supporting industries, would hardly be labor-intensive.

The urgency of developing radical new innovations and methods for societal planning, policymaking, and decisionmaking, in anticipating and regulating, controlling, and adapting to explosive sociotechnical and environmental change and reconfiguration, has been stressed by several authors including me (especially in [3]) and, I believe, Forrester [7] and Holling [27]. Holling reports on a number of environmental-management policies, all of which were "successful" in the short-run but failed in the long run. Each policy had triggered the system to evolve into one with qualitatively different properties.

Finally, can the System Dynamics National Model help fulfill these urgent managerial needs? I believe so, but I suggest the following areas of possible concern and further investigation:

1. System dynamics, expressing (self) regulation and control, may be necessary but, by not depicting emergence of new structure, insufficient for change [1], [3], [4].
2. System dynamics has traditionally contrasted itself with econometric modeling, a relatively primitive and, I believe, obsolescent but unfortunately still politically powerful methodology. "Classical" system dynamics should now look at the "other" system dynamics (the dynamics of systems), some of which has been emphasized in this paper. Perhaps new insights into improving model structure would emerge.
3. The system dynamics model, like all such models, is a sociotechnical innovation. Like weapons systems, power plants, and so on, a long lead-time is necessary between conception and fruition. Meanwhile, the real world is changing rapidly, and these changes lead modeling efforts. So far 10 years have been devoted to assembling and linking the capital and consumer sectors. This effort has produced invaluable new insights. But can the model be completed in time to deal with today's mounting crises, for example, permanent massive unemployment, national bankruptcies, and possible collapse of the national banking system? I have seen many computer programs that have become unknowable and unworkable because of superstition of modifications like the Engineering Change Proposals in hardware design.
4. Perhaps it is no longer possible to complete a complex computer simulation model of society to be turned over to "decision-makers." Perhaps the major use of these system dynamics models is as a *heuristic*, as has apparently been the case with the National Model so far, *in theory-building* and eventually in interactive problemsolving by expert advisors in business and government.
5. Perhaps some of the new constructs of system is science can be applied variously to model simplification, model completion, and improvement of model fidelity through internalization of discontinuities, structrual change, and so forth

REFERENCES

[1] De Greene, Kenyon B., 1981. "Is System Dynamics Theory Complete? -- Extensions and Interfaces." In David F. Andersen and John D.W. Morecroft (Eds.), *Proceedings of the 1981 Systems Dynamics Research Conference, Held October 14-17, Rensselaerville, NY*, pp. 118-132. Cambridge, MA: Massachusetts Institute of Technology.

[2] De Greene, Kenyon B., 1981. "War or Peace: A View from the Tightrope." In *Proceedings of the 1981 International Conference on Cybernetics and Society, Held October 26-28, Atlanta, GA*, pp. 160-165. New York: Institute of Electrical

and Electronics Engineers.

[3] De Greene, Kenyon B., 1982. The Adaptive Organization: Anticipation and Management of Crisis. New York: Wiley.

[4] De Greene, Kenyon B., 1982. "Toward an Integrated Theory of Societal Macrosystems with Special Reference to the Evolution of War or Peace." In Proceedings of the 7th International Conference on System Dynamics, Held June 16-18, Brussels. Brussels: Universite Libre de Bruxelles.

[5] De Greene, Kenyon B., 1982. "Anticipating Critical Reconfigurations in World Societal Fields." IEEE Transactions on Systems, Man, and Cybernetics, SMC-12 (5), 694-704, September/October.

[6] Gaillard, Mary K., 1982. "Toward a Unified Picture of Elementary Particle Interactions." American Scientist, 70 (5), 506-514, September-October.

[7] Forrester, Jay W., 1977. "Growth Cycles." De Economist, 125 (4), 525-543.

[8] Forrester, Jay W., 1979. "Productivity as Affected by Long-Term Economic Changes." System Dynamics Group Paper D-3139-1. Cambridge, MA: Massachusetts Institute of Technology, October 9.

[9] Andersen, David F., 1982. "Developing New Concepts in System Dynamics: A Review of the 7th International System Dynamics Conference at Brussels." Dynamica, 8(II), 113-

116, Winter.

[10] Piatier, André, 1981. "Innovation, Information, and Long-Term Growth." Futures, 13 (5), 371-382, October.

[11] Dickson, David, 1983. "Technology and Cycles of Boom and Bust." Science, 219 (4587), 933-938, February 25.

[12] Kerr, Richard A., 1983. "Orbital Variation - Ice Age Link Strengthened." Science, 219 (4582), 272-274, January 21.

[13] Graham, Alan K. and Peter M. Senge, 1980. "A Long-Wave Hypothesis of Innovation." Technological Forecasting and Social Change, 17, 283-311.

[14] Goodman, Michael R., 1974. Study Notes in System Dynamics. Cambridge, MA: Wright-Allen Press.

[15] Meadows, Dennis L. and Donella H. Meadows (Eds.), 1973. Toward Global Equilibrium: Collected Papers. Cambridge, MA: Wright-Allen Press.

[16] Mensch, Gerhard, Charles Coutinho, and Klaus Kaasch, 1981. "Changing Capital Values and the Propensity to Innovate." Futures, 13 (4), 276-292, August.

[17] Casti, John, 1979. Connectivity, Complexity, and Castrophe in Large-Scale Systems. New York: Wiley.

[18] Prigogine, Ilya, 1980. From Being to Becoming: Time and Complexity in the Physical Sciences. San Francisco: Freeman.

[19] Wilson, Kenneth G., 1979. "Problems in Physics with Many Scales of Length." Scientific American, 241 (2), 158-179, August.

[20] Nicolis, Gregoire and Ilya Prigogine, 1977. Self-Organization in Nonequilibrium Systems: From Dissipative Structures to Order through Fluctuations. New York: Wiley.

[21] May, Robert M. (Ed.), 1981. Theoretical Ecology: Principles and Applications (Second Edition). Boston: Blackwell.

[22] Day, Richard H., 1982. "Complex Behaviors in System Dynamics Models." Dynamica, 8(II), 82-89, Winter.

[23] May, Robert M., 1976. "Simple Mathematical Models with Very Complicated Dynamics." Nature, 261, 459-467, June 10.

[24] Robinson, Arthur L., 1982. "Physicists Try to Find Order in Chaos." Science, 218 (4572), 554-556, November 5.

[25] Vermeulen, P.J. and D.C.J. De Jongh, 1977. "Growth in a Finite World - A Comprehensive Sensitivity Analysis." Automatica, 13, 77-84.

[26] Abelson, Philip H., 1983. "Biotechnology." Science, 219 (4585), entire issue, February 11.

[27] Holling, Crawford S., 1981. "Resilience in the Unforgiving Society." Institute of Resource Ecology Paper R-24. Vancouver, B.C., Canada: University of British Columbia, March.