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ORGANIZATIONAL CHANGE FROM A NEW PERSPECTIVE: PATTERN FEEDBACK CONTROL IN HUMAN SYSTEMS

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Keywords: organizational change, system dynamics, feedback control, pattern feedback control

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Abstract

System Dynamics (SD) is intended to solve dynamic problems in existing living systems by achieving improved future time patterns for problematic system variables. Since the general time patterns of a system's variables are created by the system's feedback control structure operating through time, improved patterns can only be obtained by changing the system's feedback structure in ways that will produce improved future patterns. In human organizations, this restructuring of the feedback system is referred to as organizational change. Organizational change in most real human systems is achieved without the conscious analysis and the utilization of explicit feedback control principles, mathematical model building, and simulation that characterize SD problem solving. Practical SD problem solving is based on a unique philosophy of how the world works to create feedback structures and, thereby, time patterns; and a methodology for using the principles of the philosophy to change real feedback structures to achieve real improved future patterns. The recognition of a dynamic problem followed by the other parts of the change methodology may take considerable time. Intervention in the operating structure to make the changes necessary to achieve the pattern improvements may create transient patterns that both delay and interfere with the anticipated new time patterns. These realities produce complex, sometimes detrimental, time histories for important system variables during the transition from problematic old patterns to improved new patterns.

The "dynamics of organizational change" may refer to either the dynamic (time dependent) nature of the way structural changes are made in a system's feedback control structure and/or to the nature of and the difficulties associated with the transitional time patterns. Unfortunately, the SD philosophy and methodology have not been sufficiently developed in several important areas that are necessary for consistent success in achieving improved future real time patterns in real organizations. Also, the nature of the organizational change process, whether done by SD analysts or managers, as a qualitatively and quantitatively different kind of feedback control from the Newtonian/Leibnizian calculus type of feedback control used in SD analysis and programmed into SD simulation programs, has not been recognized. This paper describes some of the gaps in the SD philosophy/methodology and the nature of the new kind of feedback control, herein called Pattern Feedback Control (PFC).

1. Introduction

SD uses the concepts and the mathematics (when possible) of feedback control theory (FCT) that have been so successful in the various fields of engineering. Both the living and nonliving entities in the universe function in certain fundamental ways that automatically create feedback relationships between variables that interact to produce dynamic behavior. "Dynamic behavior" refers to the changes that occur through time in the values of variables. The inevitable creation of feedback loops that produce the behavior patterns experienced by living systems requires the SD problem solver to analyze based on the way feedback loops produce desirable and undesirable time patterns (trends, oscillations, and variations thereof). Thus, a SD analyst may be able to modify living feedback structures so they will produce desired dynamic patterns, instead of accepting undesirable patterns created by unintentional or poorly designed loops. What a SD analyst is doing is performing a sophisticated form of organizational change. Once the relationships between the loop structures and the performance patterns are understood, feedback loops sometimes can be changed, added and/or deleted to introduce desirable patterns and remove undesirable ones. In general, living systems operate to reduce the randomness and uncertainty of their internal operations and of their environments and to produce reliable, predictable, beneficial dynamic behavior.

Most SD work is problem solving in existing living systems, whereas traditional engineering mostly involves designing inanimate systems. Since the variables in living systems arise from human attitudes and activities as well as from non-human living entity attributes, general FCT concepts must be applied to the practical realities of living entity variables and their causal relationships. Most relationships between living variables are not as clear, linear, predictable, precise, and measurable as relationships between inanimate variables. In addition, living systems are self-aware, self-correcting, and internally motivated, so problem solving for existing living systems is considerably more difficult than designing inanimate systems. Therefore, SD philosophy and practice arise not only from FCT, but also from all of the disciplines whose mandate is to understand certain aspects of living system behavior. Therefore, ethics, economics, political science, sociology, psychology, social psychology, management, theology, anthropology, biology, ethology, zoology, entomology, ecology, botany, and many other disciplines are sources for understanding causal relationships between variables in living systems. Not all of these fields will be relevant in any particular SD analysis, but, in principle, SD practice is dependent on all of them. SD analysts must be sufficiently conversant with these fields, so that when a system of interest requires information from one of them, the analyst can find it. Some fields are not as focused on feedback structure and dynamic behavior as SD, so information obtained from a field may have to be interpreted and restructured to extract the proper feedback loop and dynamic pattern implications. Some fields also exclude from their analyses variables studied in other fields. Such "externalities" are often parts of important feedback loops that the SD analyst must include to understand system behavior; so SD must provide these missing links also.

Another area of SD philosophy and practice includes the elements of the SD methodology for analyzing, synthesizing, and changing living feedback systems to achieve lasting, improved behavior patterns. The patterns (trends and oscillations) of important system variables are created by the operation of the system's feedback structure through time and by the influences of exogenous input time functions. If the patterns are unacceptable, the feedback relationships must be changed to obtain better patterns, since exogenous input functions cannot be changed (by definition, they are uncontrollable). In order to obtain improved real patterns, the real loop structure must be changed properly and lastingly. SD methodology includes gathering information about the system's operations from which the important real loop structure is inferred. Information gathering about past time histories of important variables from which dominant time patterns are deduced; testing causal hypotheses; conceiving changes in the loop structure that will produce better future patterns; and modifying the existing structure are also included. These activities and analyses are based on certain principles, philosophies, mathematical procedures, human behaviors, et cetera that are fundamental to successful SD practice.

This system improvement procedure creates a new kind of feedback process, herein called Pattern Feedback Control (PFC). The SD system improvement procedure (SD's way of performing sophisticated organizational change), has not previously been considered to be a new kind of feedback control, so it has no mathematics appropriate for its analysis. In the PFC process, hypotheses about the patterns in past time histories and the dominant feedback loop geometry are used in an analysis/synthesis process to create a proposed modified geometry. The proposed modified geometry is the basis for changing the old real geometry to become the improved real geometry. After implementation and a transition period, the improved real geometry operates in the future to create new, improved patterns, thereby closing the pattern feedback loop. The old geometry (existing feedback structure) is an accumulation of structural loop relationships, so their change can only be accomplished through time as a flow of geometry change, not as an instantaneous, accurate transformation of relationships and policies. PFC has new, important properties that are not associated with ordinary accumulations and loops. An important additional complication is that the operating real structure of the subject living system is a physical manifestation of the beliefs, concepts, attitudes and visions (objectives) of the system's participants. These intangible (spiritual) mental constructs, called the collective mindset, are the basis for the creation and maintenance of the real operating structure. If the proposed modified geometry (the recommended improved loop structure) is incompatible with the system's collective mindset; either the mindset must be modified to be compatible with the improved loop structure or the improved loop structure must be redesigned to be compatible with the collective mindset, before implementing the changes. Otherwise, the implementation may be difficult or impossible to accomplish.

SD is the most fundamental, universal, and effective of all disciplines for solving problems in living systems. It uses the most important characteristics of how the world works to create dynamic behavior. It depends on the fields devoted to understanding the important characteristics of living systems. Its methodology for system improvement represents a different kind of feedback control (PFC) that is essential for effective problem solving. This paper deals with the nature and origins of FCT, and the aspects of the SD methodology that comprise PFC. These are the basis for the successful, long-term improvement of real living systems.

2. Feedback Control Theory

2.1 How the World Creates Feedback Loops

Two elementary types of essential variables operate in the world. A nonessential third type, called concepts or auxiliaries, will be discussed later. The most descriptive names for the essential ones are accumulations and flows. Accumulations may also be called stocks, levels, or integrals. Flows may also be called rates or rates-of-change. Accumulations are things, concepts, stored energy, distances, even time (often aggregations of related items) that exist at an instant of time. Flows are transfers of units from one accumulation to another through time. Flows do not exist at an instant of time because an interval of time is required for a flow to transfer units from the source accumulation to the recipient accumulation. The quantitative amount or value of an accumulation is the accumulated difference between all the units that ever flowed into the accumulation minus all the units that flowed out since the accumulation was originally created. The number of gallons of water in a lake at a particular time is the accumulated difference between all of the gallons that ever flowed into the lake minus all of the gallons that flowed out from the time the lake was formed until that particular time. The same process exists for a human body (cells flow in and out), an inventory (product units flow in and out), and the distance between your car and the one in front of you on a highway (space flows in and out based on the velocities of the two cars). The number of units in a physical accumulation is a continuous function of time (the accumulation has a quantity that may be zero or negative in some cases at every instant of time). Information about an accumulation may be discrete in time, if the accumulation's value is measured intermittently. The position (an accumulation) of an aircraft in flight is continuous in time; but the position as measured by radar is discrete. Physical flows are continuous functions of time also. Since the amount of an accumulation only reflects the actual difference between the total flows in and out, a particular accumulation's amount cannot be influenced by anything except what has flowed into and what has flowed out of that accumulation. Thus, an accumulation can only be controlled (changed) by its flows. *It cannot be controlled directly*.

A nonessential type of variable, called a concept or auxiliary, is often used to clarify concepts or to simplify equations. Things such as desired values, expected values, efficiencies, and variable delay times may be formulated as concepts. A concept has a value at a point in time based on the values of accumulations and/or other concepts at the same time. The process that creates a variable's value determines the type of variable that it is. For example, a price may be an accumulation or a concept depending on how it is determined. The prices of stocks, bonds, and commodities traded on exchanges are accumulations; while a price set by a seller as a percentage above cost is a concept. An electrical current is a flow in electrical interactions and an accumulation in magnetic processes. Sometimes, it is quite difficult to identify the types of some variables in human systems. Concepts are based on accumulations and used in flow equations. They are nonessential because the flows in which they are used can be expressed directly in terms of the accumulations.

In real living systems, the values of some accumulations must be maintained within tolerable ranges or the system will be at risk. If the finished inventory of a product from which a firm fills its orders is too small, orders cannot be filled. If inventory is too large, there may not be enough space in the warehouse to store all of it, and the cost incurred in acquiring the large inventory may deplete cash balance (another accumulation) to a point where the company cannot pay its bills. If the value of an accumulation is "important" to people or organisms; consciously or unconsciously, they will try to control it (i.e., to change it to a value that works better or that they like better). In order to control it, they must control one or more of its flows. To control a flow to achieve a better value for an accumulation, the value of the accumulation must be used in setting the flow's value. Because the flow is a rate of change of the accumulation's existing value, the flow must be based, not on the desired value alone, but on the difference between the current and desired values and the time considerations needed to correct the error through time. In contrast, concept variables, that can be controlled directly, have their values reset to the desired values without controlling a flow to correct an error through time. The indirect accessibility of accumulation values and the need for the accumulation's value to be included in the flow control, force the creation of feedback control loops.

The world works in this accumulation-flow-feedback-control way for non-PFC systems, no matter what units the variables have. In nonliving systems there may be no desired values, but feedback loops still create the dynamics. For example, the trajectory of the earth's motion around the sun is an ellipse. The ellipse arises from the balance of the gravitational and the centrifugal forces acting on the earth that creates its momentum (an accumulation of internal energy that propels a body in a given direction) perpendicular to the center of gravity of the solar system around which it rotates. If a meteor were to strike the earth with enough force to deflect it into a new elliptical trajectory, the earth would not return to its old path. However, if an inventory were deflected from its desired value, the inventory correction decisions would return it to the goal. Living systems are self-correcting feedback systems, while natural nonliving feedback systems often are not self-correcting. Nonliving feedback systems designed by humans (servomechanisms) often are self-correcting. The world works in this accumulation-flow-feedback-control way to create dynamic behavior whether humans exist or not and whether humans understand it or not. It works that way for the whole universe, including the solar system, the Earth, and humanity.

2.2 How Feedback Loop Structures Create Time Patterns

Whenever a flow into or out of an accumulation is influenced by the accumulation's value, a feedback loop is created. A feedback loop is a closed sequence of causal relationships. Thus, the flow influences the accumulation; and, later in time, the accumulation or information about it influences the flow. The inaccessibility of the accumulation, except to its flows, forces indirect control through its flows. This inevitably results in the creation of feedback loops. The geometry of the loops (the interconnected closed paths of causal forces that influence the variables) operating through time, combined with the magnitudes and delays of the individual causal influences in the loops creates the time patterns that are experienced by the system's variables. The patterns arise through the reinforcement or opposition of changes in variables in a loop that occurs when the causal influences are closed later in time.

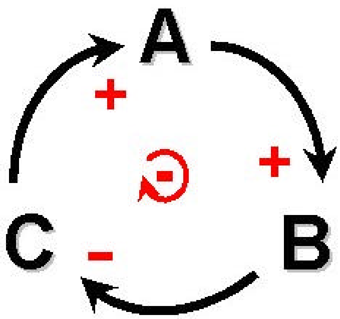

Figure 1a. Single Feedback Loop

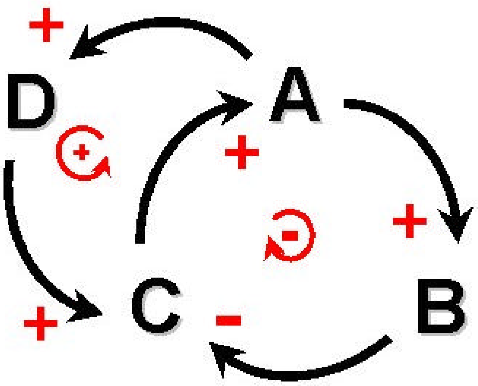

Figure 1b. Two Connected Loops

Figure 1a is a causal loop diagram for a single feedback loop with three variables, A, B, and C. The arrows represent causal influences of the arrow end variable on the arrowhead variable. The algebraic sign (+, -) at the arrowhead indicates whether the dependent variable (arrowhead) changes in the same direction (+) or the opposite direction (-) as the causal variable (arrow end). If variable A were to increase in value at some time, B would also increase; but later in time. After B increases, C will decrease. The decrease in C, later will produce a decrease in A. Thus, the loop is closed with the original increase in A being opposed later in time when the loop influences return to A. The loop in Fig 1a is negative because the product of its arrow signs is minus. Negative single loops oppose changes in loop variables and produce stable or oscillatory patterns. Single positive loops reinforce changes in loop variables and produce stable or exponential patterns (escalating growth or decline). In Fig 1b, two loops are connected (coupled). The new loop with variable D is positive. Here if A increases, it may continue to grow, or oscillate, or stay the same, or grow and oscillate. The resulting pattern will depend on the specific details of the combined actions of the individual causal relationships; so the behavior of feedback systems may be very difficult to understand. In any case, <u>the value of a variable in a feedback system at a point in time is the value of the variable's time pattern at that time</u>. It is not an independently created value for that time. The whole system process creates the pattern, so the value cannot be modified effectively by actions or decisions focused on that variable alone or that time alone; the whole system must be considered through time.

2.3 Mathematics for Dynamic Analysis: Calculus and Feedback Control Theory

The operation of a simple, one-accumulation feedback system is easy to understand without mathematics; but when a system has many accumulations and many loops, understanding its operation becomes much more difficult. Then mathematics is very helpful in obtaining solutions to problems and in clarifying the way systems actually work. Dynamic behavior is the essence of life and human well being. Dynamic behavior arises from the intrinsic accumulation-flow-feedback-control organization of the world. Therefore, any methodology that is able to understand, analyze, and improve the dynamic patterns produced by feedback systems, no matter what units the variables have, is the most fundamental, universal, and effective for solving dynamic problems. Recognition of these principles combined with the mathematics necessary to design and analyze such relationships with precision has led to the explosion of technology since the mid-19th century for designing physical systems.

To represent mathematically the most elementary feedback interaction, two kinds of equations are needed. The first equation must represent the way flows cause an accumulation to change. The second must represent the way an accumulation causes a flow to change. In the first equation, in which the accumulation's value at time t equals a function of the flows, two problems must be solved. Firstly, the accumulation's value must be based on the entire past history of the flows, not just their values at time t. Secondly, while the accumulation has a value at time t, the flow values at time t (or at any instant of time) are zero because a time interval is needed for units to be transferred to an accumulation by a flow. Writing the second equation involves the use of algebra and, sometimes, logic functions. Algebra was invented before 1500 B.C. in Egypt, Sumer, India, and China; later, Greeks and Arabs improved it. Logic functions were developed recently.

In the 1680's Isaac Newton (1642-1727) and Gottfried von Leibniz (1646-1716) solved the two problems associated with accumulation equations independently and almost simultaneously by inventing calculus. Calculus provides the notation and method for adding together (integrating) continuous flows <u>and</u> providing the small (infinitesimal) interval of time (the differential, dt) to allow the flow to transfer units. Both invented the integral and differential versions, though Leibniz emphasized the integral calculus that represents the way real flows are accumulated in the world, while Newton emphasized the differential calculus that gives the same numerical answers; but uses an artificial operation that the world does not perform, differentiation. Since calculus is the fundamental mathematical basis for dynamic analysis, engineering universities require their students to study it and its dynamic-problem solving method, differential equations. Today calculus is taught in its differential form because it is computationally easier. Integration is called anti-differentiation. However, the integral form is very important because, when an analyst must design or analyze a system that is too complex for solution of its differential equations, the analyst's understanding of the system's real feedback structure becomes critical for proper analysis. One cannot understand a system without clearly identifying its accumulations and how control must be exercised through information or forces originating at the accumulations that feedback to the flows.

When a system has more than one accumulation (n) to be controlled, there will be an integral equation for each one. When these are combined with the control influences from the accumulations to the flows and manipulated to isolate a single equation for the variable of interest, a differential equation with n+1 terms and a highest derivative of nth order is obtained. Solving differential equations to obtain the closed-form time function responses of the variables of interest was the way quantitative dynamic analysis was performed (with considerable difficulty) until the late 18th century. Then, Pierre-Simon de Laplace (1749-1827) devised the Laplace transform method (LT) for solving linear differential equations. The LT is an operation imposed on each term of a differential equation that changes the mathematical form of the term from a derivative to an algebraic function. It also changes the independent variable for the analysis procedure from t (time) to s, a complex variable with units of 1/time (frequency). In Laplace's frequency (s) domain, functions are manipulated algebraically, instead of being convolved in time. Convolution is a complex integration over the life of the system of two time functions that are multiplied together. The LT made solving differential equations easier and facilitated the analysis of more complex, higher order systems. James Clerk Maxwell (1831-1879) published the first mathematical analysis of a feedback system (*On Governors*) in 1868, though many people had verbally conceptualized simple closed-loop processes before that time.

In the early 20th century, the feedback control geometry of differential equations was explicitly recognized. Then, the physical meanings of the LT and its complex frequency variable, s, were perceived. Separation of the system's contribution from the contributions of exogenous inputs to the output time patterns was achieved by inventing the impulse response of the system, and then deriving the convolution integral. The convolution integral finds the product of the impulse response function and the input time function for an infinitesimal instant of time, dt, and adds up all of the contributions from all past impulse responses to find the output time function. Usually, it is quite difficult to solve the convolution integral. However, the Laplace transformed counterpart of the impulse response, the transfer function, can be multiplied by the LT of the input function in the frequency domain to get the LT of the output function by using algebra instead of integration. The ease of mathematical manipulation in the frequency domain ushered in the era of feedback control system analysis and design using LTs in the s-plane. The primary design feature of engineering systems became the frequency response, such as the one you might receive when you buy a high quality audio amplifier or CD player. Since electrical, mechanical, and other systems designed by engineers had to be stable (i.e., be free of positive exponential time function responses, so the systems did not malfunction or self-destruct when the exponential values became very large), the primary design problem became achieving stability.

As the 20th century progressed and the digital computer was invented, discrete time representations of accumulations and flows were provided by difference equations (discrete time integral equations). The problem of noise (random variations in the time functions of systems' inputs and outputs) was addressed by representing noise in the frequency domain and developing methods of filtering and modulating in time to remove or reduce it. For problems in which the statistical characteristics (randomness) of the input time functions dominated their deterministic characteristics, auto correlation and cross correlation functions of variables were transformed to the frequency domain instead of time functions. These were called power density spectra. Using these power density spectra, systems could be designed to provide improved statistical behavior.

Approaches to the optimization of a system's performance were discovered in the 20th century. Optimization methods provide optimization algorithms that take the system equations and the objective function for the system and derive the optimal solution. This is an input function that produces an optimal output time function or the transfer function of a compensation-network that is added to the system structure to produce an optimal output time function. Unfortunately, optimization methods are unable to provide practical optimal solutions for dynamic problems in most real living systems. Living systems are too complex and nonlinear for solution of the optimization algorithms, and real living systems' objective functions usually do not fit the required format of minimization of mean squared error between desired and actual output time functions. However, these methods work well in engineering systems. People could not have been transported to the moon and back without them. FCT includes all of the above concepts and its mathematical methods are used to analyze and synthesize dynamic systems.

Human beings create self-correcting engineering and social systems that are intended to be as isolated as possible from the random variations of weather, electromagnetic static, natural world irregularities, and human inconsistencies as possible. Thus, the emphasis in FCT is on the deterministic aspects of behavior. Since stochastic processes exist, analyses of noise and of stochastic properties of systems is considered in the writing of causal equations for variables with noise and in the analysis of stochastic system performance. The mathematical principles and methods of FCT are independent of the units of the subject system's variables and are based on the most fundamental aspects of the way dynamic behavior is created. Therefore, the calculus-based design of stable, deterministic, dynamic systems with noise reduced or removed is the primary practical theme of modern mathematics and engineering. It is a universal analysis tool. SD is the logical heir of these powerful and universal principles and methods of science for the most important of all problems: the survival and well being of humanity. However, when the subject system contains living variables and the control functions arise from human attitudes and perceptions and from the attributes of non-human living entities; the simple, quantitative application of FCT, that is so successful in engineering systems design, becomes much more difficult.

3. Philosophy of the System Dynamics Methodology

3.1 Living System Complications

Living systems are nonlinear and complex (i.e., have many accumulations and loops), so their models result in high order, nonlinear differential equations. The Laplace transform is not defined for nonlinear functions, so nonlinear differential equations cannot be solved with LTs. Some simple nonlinear differential equations can be solved with other methods, but nonlinear living systems usually are not of these types. Even linear differential equations can only be solved explicitly for all systems up to fourth order because there are no general solutions for algebraic equations of fifth and higher orders. When the individual first-order accumulation equations are put in matrix format and solved for characteristics other than their time functions (e.g., stability, controllability, etc.), solutions may be obtained for higher order systems, but not as high order as needed for most important living systems. In engineering, systems can often be partitioned, so some parts can be analyzed separately or redesigned to reduce the order. FCT is seldom used explicitly to design living systems with specific dynamic responses and stability criteria. In fact, living systems are often deliberately intended to be unstable. Instead, SD is used to study and to correct problems in existing living systems that the SD analyst did not design. Thus, the analyst may not know what the important variables are, what the historical time patterns are, nor what the equations of the causal relationships are for the system. These limitations often make it difficult to construct reliable quantitative models of living systems, to partition living systems for simpler analysis, and to obtain closed-form time histories of model behavior. Therefore, time solutions must be obtained from model simulation, not equation solving; so model analysis must be intuitive, rather than algorithmic. Since living systems are self-aware, self-correcting, and internally motivated, it is not easy to impose system modifications on the participants nor to prevent them from changing their own systems to neutralize or oppose the analyst's changes. Even gathering data about a system or asking questions of the participants may induce changes in the operating feedback structure. The complexity and lack of clarity and precision of the living relationships requires the analyst to exercise a great deal of judgment in using FCT principles to improve living systems. Thus, SD is a science-aided art, rather than a true science.

3.2 Disciplines that Study Important Aspects of Living Behavior

In order to include, correctly, the important characteristics of a living system selected for SD study, an analyst must be trained to obtain help with problem formulation, analysis, synthesis, and implementation from disciplines that specialize in the study of the various properties of non-human and human living systems. While an analyst's personal observation and experience are important, living behavior is too complex, hidden, unmeasurable, “irrational,” deliberately deceptive, and unconsciously determined for simple observation to be enough. Thus, there are many disciplines whose principles must be included in SD studies of human systems. “Human” oriented disciplines study the separate and coordinated operations of the physical, mental, and spiritual aspects of individual humans and of human groups, as well as all separate and coordinated aspects of artifacts, organizations, and systems created by humans. Thus, the automobile, the U.S. Interstate Highway network, air pollution in a city, and the oil industry are all human systems, both individually and as parts of a coordinated, motorized, transportation culture. Therefore, there are many disciplines that have been created to study humans and their products. Among these are all of the physical sciences (technology is a human artifact), economics, political science, sociology, psychology, social psychology, biotechnology, medicine, epidemiology, etiology, gerontology, mythology, musicology, management, anthropology, ethnology, history, philosophy, ethics, epistemology, theology, parapsychology, criminology, and military science. Human beings are so complex, and they have created so many different artifacts, organizations, and systems, that there are many other fields and disciplines that contain important information and methods that would be necessary for SD analyses of some human and general living systems.

Some of the above disciplines, such as medicine, psychology, and philosophy, originated thousands of years ago independently in several different cultures. Successful brain surgery (trephining) was practiced more than 10,000 years ago in the Middle East and in the Far East. Many other disciplines are of more recent origin. Genetic engineering (1960’s) could not exist until DNA was discovered in 1944. As time passes and more and more is learned, both benefits from the new knowledge and questions that could not have been conceptualized before arise. The questions lead to increasing specialization (topics with smaller scope) and in some cases to combining specialties. Thus, criminology (1890’s) is a recent subcategory of sociology (1840’s), itself a product of philosophical thought originating in ancient times. Epidemiology is a recent (1860’s) specialty of medicine. Histochemistry (1860’s) combines the techniques of biochemistry (1860’s) and histology (1840’s) to study the chemical constitution of cells and tissues. Therefore, SD, when it studies the feedback control dynamics of living systems, is dependent on an understanding of the concepts of FCT and on information from many disciplines that study the properties of the inanimate, living, and spiritual forces in those systems. As the size, complexity, and importance of living system subjects for SD analysis increase, the necessity for a truly professional coordination of related specialized disciplines with the SD philosophy and methodology also increases.

3.3 System Dynamics Methodology for Creating Improved System Performance

Given the major difficulties inherent in observing, analyzing, synthesizing, and implementing solutions in real living systems, it is important to have a systematic, effective methodology for solving problems in such systems. Such a methodology must be able to do the following things:

1) Observe, as quantitatively as possible, past and present operating procedures, decisions, and structures, exogenous input variables, and time histories of exogenous inputs and endogenous system variables (those that interact with each other in the feedback control structure) without interfering with the system’s current operations or changing the loop structure.

2) Identify from past time history data and perceptions the important (problematic) time patterns in the time histories and hypothesize the feedback loop structures that create these patterns.

3) Apply effective quantitative and qualitative measures that test the accuracy of pattern identifications and the validity of causal structure hypotheses. Where possible such testing should be based on quantitative model(s) of the system relationships and statistical design of

experimental procedures for determining the schedule of model simulation experiments.

4) Synthesize changes in the operating structure and its parameters that will produce improved time patterns for the important system variables. This may require modifying the perceived loop structure to include loops that will become important when the operating structure is modified or when the modified structure is in normal operation after the transition dynamics.

5) Analyze the transition period dynamics to determine the magnitude and duration of any adverse conditions as a function of timing and order of implementing structure changes.

6) Develop a plan of implementation that specifies when, where, how, by whom, and for whom the structure changes are to be implemented; and how unwanted changes are to be avoided.

7) Develop a procedure for administering the implementation plan in an efficient, timely manner to properly modify the real system's feedback structure.

8) Continuously review the progress of the study, to identify errors in any part or result of the procedure, and to determine when new structure changes are needed.

9) After improved performance is achieved, to continue to evaluate the system to recognize conditions that require additional structure modifications. SD evaluation should continue on a long-term basis as an integral part of the system. SD is not effective as an intermittent consulting activity.

This procedure produces a new kind of feedback structure, Pattern Feedback Control (PFC). It is a higher order kind of feedback in which information and perceptions about system operations are used to hypothesize dominant feedback loop geometry. In addition, information and perceptions about past time histories are used to hypothesize the time pattern characteristics of important variables. These hypotheses are tested and used in an analysis and synthesis process that results in the modification of the feedback structure to produce better time patterns in the future. Normal feedback control uses information about the values of important variables at a point in time to influence the values of other variables at later times to produce better values for the important variables at future points in time. However, SD recognizes that the value of a variable at a point in time is not an independent value established for that time. The value is the value of the variable's time pattern at that time and the pattern is created by the loop geometry. For example, suppose a population of people has been growing at 2% per year and today the population is 6 billion. In 35 years, the population will be 12 billion, if the 2% growth trend pattern persists. The 12 billion does not arise at random 35 years from now. It results from reproduction, socioeconomic, and biotechnology loops operating over the 35 years starting with 6 billion. If it is considered undesirable to have 12 billion people in 35 years, some of the loops (the loop geometry) must be modified to operate differently, so the growth trend (the pattern) does not persist.

Humans exercise Pattern Feedback Control, also. However, they are usually less sophisticated than trained SD analysts. Suppose a professional football team has lost the majority of its games for several years. The owners and fans are unhappy because they consider that kind of performance pattern unacceptable. There are several things that the team owners and coach might do to improve the performance pattern. They might buy some better players, try some new plays, et cetera. One of the things that teams often do is to fire the coach. Since the coach designs and manages the feedback control system that regulates the team's operations, hiring a new coach means creating a new feedback control system for the team. Since a team control system is quite complex, it takes awhile to change it, and it takes more time before the improved performance is realized. The new coach is not usually expected to lead the new team to victory in a majority of its games for several years. And the new coach's contract usually reflects that awareness. The owners who fire the coach may not examine the details of the old coach's control system. The persistent losing performance may be sufficient grounds for termination. In that case, only performance pattern may be observed, while loop geometry is ignored. More perceptive owners may try to understand why the old coach was losing, so they can select a new coach who will not make the same mistakes. Please notice the difference between a focus on winning one particular game and on consistently winning a majority of games season after season. Many people consider only the former; SD concentrates on the latter. If a process can be designed to do the latter, the former automatically will be satisfied.

3.4 Observation and Measurement of the Subject System

SD is a conscious, professional, feedback-system-modification-to-improve-time-pattern-performance philosophy with a series of specific activities that it uses to close the pattern control loop and, thereby, to improve the real time patterns of important system variables. The effectiveness of each of the activities is important for successful improvement. The first activity is system observation. The operation of a system's feedback structure through time creates the time patterns (trends and oscillations) of its variables' time histories. Therefore, there are two aspects of a system that must be observed: the past time histories of its variables and the way the system's relationships and policies operate. In living systems, often it is not clear what the variables are, much less, which ones are important, and how the variables interact with each other. Even in inanimate systems, it may be difficult to identify the critical variables. For example, electrical variables have only been defined and measured in the last 150 years. Living beings observed lightning in the sky for hundreds of millions of years without knowing what it was. Human beings observed it for hundreds of thousands of years before Benjamin Franklin (1706-1790) started experimenting with lightning in 1747. James Clerk Maxwell (1831-1879) wrote the electromagnetic field equations (Maxwell's Equations) in 1864 upon which our electrically powered global civilization now depends. The necessity to define variables clearly and to measure them precisely, arises from the general principles of science that require reproducible experimentation with physical bodies and forces to determine the quantitative nature and dimensional consistency of the cause/effect relationships between the variables. The precision of the measurements and repeated experimentation are necessary to determine the statistical reliability of the mathematical equations that represent the relationships.

Some physical variables in living systems are fairly clear. The number of animals in a living group, the average amount of food and water per day needed to sustain individual animals, the number of predators in an area, the amount of food in storage by an individual or group, et cetera, are fairly obvious and measurable. Many characteristics of human artifacts and organizations are also clear. However, there are some variables that, while known to exist, are not easily measured because the units of measure have not been defined and there are no instruments to measure them. Almost all human emotions (love, hate, anger, fear, joy, greed, jealousy, compassion, sadness, guilt, depression,…) and many attitudes and goals that follow from them (trust, faith, aggression, deceitfulness, covetousness, vengefulness, selfishness, loyalty,…) are not easily measured. Many languages have words that distinguish degrees of some of these (e.g., like, love, adore; and annoy, vex, anger, enrage), but this is not precise enough to study the effects these mental states have on system behavior. Many of the biology, psychology, sociology, biochemistry, bio-electrical, and genetics oriented disciplines are working on measures for such forces and on instruments to measure them. The measurement of group attitudes through the use of questionnaires that are designed and administered based on statistical principles is sometimes fairly accurate. Thus, on election days, news networks administer exit questionnaires at polling places. From these they can predict with remarkable accuracy the identities of the winning candidates shortly after the polls close, long before the official vote totals are released. Since SD studies living behavior, it must be able to identify the important living variables, measure them, and relate the measurements to cause-effect relationships in a system's feedback loops. The disciplines that define the critical living system variables, develop the ways to measure them, and quantify the causal relationships between them are important for SD.

The observation of operations and relationships by an analyst is not always easy. The presence of the observer may cause those who are being observed to change their behavior consciously or unconsciously. Therefore, the observer may not see normal behavior and may draw wrong conclusions about the operations. Even if the system participants do not alter their behavior, the observer may not know what causes the people to do what they are doing. Many loops close in decisions made in people's minds. How does the observer see into a person's mind? If the analyst asks a question, will the answer be true and relevant? How can the observer be sure? Even if the observer accurately perceives what is happening and why it is happening, it still may not be clear which activities are important for understanding the origins of the performance patterns. The feedback loops may not be obvious. Even if the feedback loops are obvious, it may not be clear which loops are dominant and which are unimportant. The observer is interested in the essence of dominant control, not in compiling an exhaustive list of loops. It is even more difficult to determine how long the current loops have been dominant. Many things can change the loop structure, so it is critical to estimate whether the current loops created the observed time histories. In the end, the observer must be very perceptive and have the experience needed to make good judgments about the people and operations and the historical stability of the feedback structure. SD does not emphasize such skills.

Some human organizations collect quantitative data about their operations. In a subject system, there may be historical records for the number of employees, sales, inventory units, money, machines, and customers that a firm had at certain times (often weekly or monthly) in the past. Even when there are quantitative measurements, they may not be reliable. Sometimes data errors are introduced by accident, sometimes by intent, sometimes by ignorance (using measuring devices incorrectly or using sampling methods improperly), and sometimes by natural or human disasters, such as floods, fires, hurricanes, and thefts, that may destroy the data from long periods of past history. It may take considerable research and judgment to determine how reliable certain data are.

Notice that much of the basis for SD practice has its roots in mathematical statistics. The systems under study have stochastic aspects of their time histories and of their operating relationships. Noise (randomness) exists to some degree almost everywhere. One important reason for creating human systems is to reduce the harmful effects of randomness (uncertainty) on everyday living. Thus, feedback control theory considers both deterministic and stochastic signals. Synthesis methods consider system modifications to filter, to suppress, to mask, and to modulate signals to avoid noise. Models of relationships are hypothesized. These are tested through simulating the models' time histories under a variety of conditions. Each deterministic simulation or group of simulations with noise is an experiment in the hypothesis testing procedure. Statistical methods should be used to design the experimental procedure. When sampling system data to estimate parameters and empirical relationships between variables, statistical theory is needed. The SD literature does not dwell extensively on statistical methods, but SD analysts who study real systems with the intention to improve their behaviors should use statistical methods at many stages of their studies.

Since there are no simple instruments to automatically measure some variables in a living system, the analyst must use creative techniques for some measurements. The analyst may observe what the beings do, personally measure their activities, interact with them to see how they respond; and, if they are human beings, ask them questions, administer questionnaires, and even conduct Delphi procedures to obtain information. One of the great differences between living and nonliving beings is that living beings are aware of their observers, so they may respond in various ways to that awareness. In a natural ecological setting, animals may run away from their human observers. Even if they do not run away, they may alter their behavior in response to the observer's presence. The animals may discontinue their normal activities to watch the observer, as the observer watches them. Jane Goodall had to follow a chimpanzee troop in their native African habitat for 18 months before its leaders accepted her. Only then could she take notes to record behavior that she considered representative of their natural activities. It took Diane Fosse nearly as long to be accepted by a family of gorillas in their native African rainforest. Chimpanzees and gorillas are humanity's two closest living animal relatives. Humans share 98% of their genetic code with each of these two species. Much of the unshared 2% of human genes control higher-order cognitive activities in the neo-cortex that make humans more difficult to observe than these two great apes.

In human settings, there are many other types of responses to observation other than running away and looking back. Humans will wonder why they are being observed. If they are told why, they may not believe the reasons. They may change their activities to convey information about their behavior that they want to be recorded, rather than what they normally do. They may become aggressive to drive the observer away. They may move to a different place or create obstructions to interfere with observation. They may ask questions to distract the observer. If the observer asks questions, they may not answer at all or they may not tell the truth. Sometimes in SD studies, a question that the analyst asks causes the subjects to think about the way they operate their system with a new perspective. They may even change the way they do some things based on the new insight. The important conclusion is that it is not easy to observe what a living system is really doing or to determine what the time patterns have been in the past. Nor is it easy to observe a system without changing the way it operates, nor to know whether operations have changed as a result of your observations. SD has not invested much effort in solving these problems.

3.5 How the Observations Are Used to Develop a Dynamic Hypothesis

The two kinds of observations, time histories and system relationships and operations, are handled somewhat differently. Time histories are often complex combinations of noise (random variations) and more deterministic patterns, trends and oscillations. Time history observations and data are used as the bases for determining what major time patterns are included in the time histories. Depending on the dynamic problem, one or more of the constituent patterns may be of interest to the analyst. Since the data are simply values of the variables at points in time, there are no mathematical equations for the time histories. Therefore, extracting the patterns may not be easy, if there are many overlapping patterns and randomness present. There are mathematical methods for approximating time history data with an equation and for estimating the frequencies at which a time series has considerable energy. However, unless the data are quite regular, the confidence in the approximations and estimates may be poor. For example, the time history for world human population is a fairly clear hyper-exponential. A hyper-exponential is an exponential time function whose growth rate is also exponential. For a normal exponential, the doubling time for the function is constant. The doubling time for a hyper-exponential gets shorter and shorter. In A.D. 1500, the doubling time for world human population was about 650 years. Now (500 years later), the doubling time is about 35 years. As a physical accumulation, it is a smooth curve with little noise. Even wars and plagues, except the worldwide Black Death in the 14th century, did not affect it very much. The population time history is long (hundreds of years) and the pattern is clear. On the other hand, a daily time history for the price of a particular commodity future, say the December 2000 S & P Stock Index, has many complex patterns along with a great deal of randomness. Determining its constituent patterns is quite difficult. Procedures for extracting the constituent patterns from complete time series have been developed in the mathematics, statistics, economics, and pattern recognition fields. Most of these procedures do not identify with high reliability the patterns in real time histories with complex pattern compositions. Thus, the analyst must use a variety of quantitative and qualitative methods to develop and test hypotheses for the pattern content; and must rely on his/her own experience, system understanding, and judgment to decide which pattern hypothesis is correct. SD does not devote much effort to pattern recognition theory.

Observations about system relationships and operations and the time patterns extracted from the observed data time histories are the two bases for the SD way of determining which feedback loops dominate in creating the time patterns of interest. Since the real system usually contains a great number of loops, many of which do not directly create the important patterns; the analyst must eliminate many of the non-dominant loops and variables. There is no algorithmic way to do this. It requires informed judgment that arises from long experience in studying systems to conceptualize this hypothetical dominant system. Since such judgment is sometimes in error, a procedure has been developed to test the judgment. The analyst's mental model of the dominant loop structure and how it creates the important time patterns is described in detail in writing. This written description is called the Dynamic Hypothesis.

3.6 Testing the Dynamic Hypothesis

The Dynamic Hypothesis description is converted into a mathematical model of the hypothesized system. This is not a model of the real system. In fact, it is known and intended to contain errors because a considerable part of the real system may be omitted deliberately. The parts of the system that are omitted may be whole variables or even larger parts of the system. Another kind of omission arises when many similar entities or operations are aggregated together to form a single variable or sector. An inventory with 200 similar, but distinct, catalog items might be modeled as a single variable that represents the 200 items combined, instead of writing a separate equation for each of the 200 items. Such omissions are essential to reduce the size of the model enough so that the analyst can understand it. A thorough understanding of the model is essential because the analyst will have to judge its validity and use the understanding of its operations to create changes in the structure that, when implemented, will improve the system's time patterns. However, this simplicity and understandability is obtained at the expense of literal accuracy. Most living control operations are imprecise enough so the aggregations do not affect the essence of the way control is exercised in the loop structure to produce the patterns. However, the analyst must consciously consider this trade off between literal accuracy and understandability and perform analyses as necessary to justify the level at which the aggregation is established. It takes much experience and perceptiveness for an analyst to become skilled at selecting the appropriate level of aggregation quickly and correctly. Relatively few SD studies are carried through to the creation of improved patterns in the real system, so SD analysts rarely discover errors that they made in the analysis.

Once the equations for the hypothesis are written, there are two kinds of analysis that the analyst performs to use the model effectively. The objectives of these analyses must be understood clearly because they are not the same as the objectives of model analysis in the physical sciences. In the physical sciences, models are intended to represent the quantitative operation of the cause/effect mechanisms of the physical processes. Since they are accurate representations of reality within a small experimental error, the models (equations) stand on their own and can be used by anyone who is representing the mechanisms the models represent. Thus, Ohm's law says E=IR. The voltage (E) across a resistive element in an electrical circuit is equal to the current (I) through the resistance times the resistivity (R) of the resistance. Ohm's Law can be used with confidence by anyone, anywhere that is designing an electrical circuit with resistances. Ohm's Law is not an hypothesis any longer because it has been verified many times. The models of dynamic behavior of other circuit components (capacitors, transistors, diodes, microchips, etc.) are equally well supported. Thus, when such circuit elements are arranged in a circuit, the equation for the circuit can be written easily and solved mathematically without the analyst understanding the details of how the components work. Many electrical engineers do not know that the circuits they design are feedback control systems because they have not had to identify the loops to analyze the circuits.

Human systems have so many possible sets of relationships that are so poorly understood and so hard to measure in situ that generic models of human systems are unreliable. For each human system that has a dynamic problem, the analyst must identify the unique, dominant loops that create that particular problem. In most of such cases, a small number of critical loops at the level of aggregation of the actual exercise of control create the problematic time patterns. The analyst must be able to sort through all of the unimportant details and identify the loops that really cause the problems. Thus, the SD analyst must identify the essence of the control process that causes the problem BEFORE analyzing the system. If the analyst tries to represent accurately in detail everything in the system and expects the mathematics to find the essence of control, he/she will become hopelessly lost in thousands of equations at all levels of aggregation. That is why the development of the Dynamic Hypothesis is imperative and the philosophy of model analysis must be different from that used in the physical sciences.

Since it represents the analyst's perception of the essence of control, not complete and accurate reality, a SD model is a tool to test and to refine the perception. This is critical because the complexity and nonlinearity of living systems preclude the solution in closed-form of the model equations and the algorithmic synthesis of improvements. Thus, the analysis and synthesis must be performed by the analyst's mind, not by the computer. To prepare the analyst's mind for these tasks, the model must be exercised (simulated under different conditions). The two aspects of model testing are model validation and hypothesis verification. Validation attempts to align the model with the essence of real system control. Hypothesis testing attempts to align the analyst's mental model with the quantitative model and to verify the analyst's understanding of the dynamic properties of the model. Validation involves both statistical testing and logical exploration of both model structure and performance time patterns. When validation and hypothesis testing are "accepted" as having aligned the model to the essence of reality and the analyst's mental model to the validated model, analysis ends. At this point, the analyst's mental model is assumed to be the same as the essence of reality, and the analyst's mind understands the entire range of performance behaviors.

Now, the analyst personally must convert the system's relationship observations and time pattern characteristics, both past and desired in the future, into proposed changes in the existing dominant loop structure. If these changes are implemented correctly, they should produce a modified real loop structure that will create the desired time patterns in the future. To do this extremely difficult task in his/her mind, the analyst must understand how the system's dominant loop structure works to create the unwanted past time patterns. He/she must also know what kinds of feedback structures will produce the desired patterns, and how the system's participants will respond to the changes in structure and to the new patterns. SD has not developed well the principles of performing such a difficult and critical task successfully and consistently.

3.7 Synthesis: Finding Changes in the Feedback Structure that Produce Better Time Patterns

The analyst accomplishes the difficult task of synthesis by doing things that stimulate and assist his/her unconscious creative mind as it works to produce the synthesized new structure. One of the important tasks is to specify the future time patterns that are desired. Another is to modify the mathematical model that represents the analyst's hypothesis for the dominant loops that created the unwanted past patterns. That model may not include some feedback loops that will become important when changes are made to the operating structure. The behavior of the modified model is then simulated for carefully selected sets of conditions. Each set of conditions is chosen to clarify for the analyst some aspect of the way the model's loops work to produce specific aspects of the desired future time patterns. The analyst's mental model, rather than the mathematical model, is the important model because the determination of the improved system structure (the solution to the dynamic problem) is done in the subconscious mind of the analyst based on the mental model, not in the computer based on the mathematical model. Therefore, the analyst and others must be careful to use the model in the way intended.

Once the analyst's subconscious mind has produced a proposed solution (modified loop structure), the analyst must test its acceptability. The proposed modified structure must be written down in words to become a dynamic hypothesis for the improved structure that will create the desired time patterns in the future. The same hypothesis testing procedures described above are now used to bring the analyst's mental model of the improved structure into alignment with the model structure that has been able to produce the future desired patterns. This is done to verify that the modifications provided by the analyst's subconscious mind are, indeed, capable of producing the desired patterns. Unfortunately, even if the hypothesis testing procedures verify the usefulness of the proposed modifications, other constraints on the modifications must be considered before the modifications can be accepted.

These considerations include the following:

1) Are the proposed modifications realizable physically, biologically, financially, organizationally, and in human behavior terms? The proposed changes may involve physical changes in facilities, available resources, or personnel; or changes in the biological characteristics of an ecosystem, work animals, or the flora and/or fauna of an area. The proposed changes may require raising money to pay for the changes; changes in the way organizations work or are administered; changes in the way laws are made and enforced; or changes in the ways that humans behave, make decisions, and interact with others. The details of how the changes may be accomplished in these and other areas must be acceptable. If any are not, the creative exercise must be repeated. There are usually many different structures that could produce the desired patterns. However, each structure will have different effects on the considerations above. Since human systems have many evaluation criteria to satisfy simultaneously, the choice between two proposed modified structures may be very difficult to make.

2) Is the model of the system's original Dynamic Hypothesis adequate to represent the behavioral contributions of the unchanged parts of the system to the future patterns of the modified system, both during the transition period and after the new patterns appear? Unless perceived otherwise, the model to be used to evaluate the effectiveness of the structure changes is the same as the model that was used to represent the analyst's perception of the essence of the control system that caused the problems. However, in many studies, parts of a system that were omitted as unimportant in understanding the problem, become important in the context of the changed system. Thus, the analyst must reconsider the original dominant structure in light of the characteristics of the transition period and the proposed improved system. Often, some parts of the system that were omitted must be added to the model. In some severe cases, the entire model must be reorganized or the model's level of aggregation must be changed

3) Will the transition dynamics during the implementation of the changes be acceptable? When the feedback structure of a system is changed in the midst of its operations, the time patterns of its variables change from the past undesirable patterns to new patterns that are neither the past patterns nor the expected desired future patterns. These patterns are called transients, patterns that exist for awhile then fade away to reveal the improved patterns that the modifications are intended to produce. The period of time over which these transients are dominant is called the

transition period. It is much like the period of convalescence a person experiences during and after surgery to correct an illness. In many human systems, transition period conditions can become worse than those of the past illness and worse than the future improved state. The decision of the system to undergo the surgery is based on an evaluation of whether the improved conditions after surgery are expected to be enough better than the ill condition to make the costs and risks of the surgery and recovery worth accepting. This choice can be partially clarified, if the transient dynamics are estimated through a transition analysis. In this analysis the model of the old system is simulated with the changes in structure introduced at the times expected in the actual implementation. This is a guide to what will happen in the transition period, if the structure changes are made as planned. Of course, if the real changes are not actually made in the ways and at the times anticipated in the simulation, the real transition patterns may not be the same as the simulated ones. While subject to error, transition analyses are very helpful in guiding system participants and analysts to avoid errors and to know what to expect. SD analysts rarely do transition analyses and there is little in the SD literature about such an analysis.

4) Will the implementation of the proposed structure changes induce undesirable, unauthorized structure changes initiated by individuals or groups inside or outside the system? Living systems are neither unaware of nor passive to attempts to change their structure and behavior. Sometimes the intent to change a system by one group induces others to change the system for or to protect their own interests. Living systems, especially human systems, sometimes change the structures of their systems even when no one else is trying to change it. Darwin’s theory of evolution explains how characteristics of species change “unconsciously,” through natural selection, to improve the survivability of the species in its environment. Structure changes induced by the implementation of proposed structure changes can sometimes be violent and reverse the intent of the proposed changes. Prohibition in the United States was a classic example of such an anomaly. The manufacture, sale and distribution of alcoholic beverages was prohibited in 1920. Reformers wanted to reduce alcohol consumption to improve individual health, family wellbeing, and social stability. In fact, the consumption of alcohol greatly increased and organized crime became oppressive. This experiment failed miserably. Many people simply refused to obey the Volstead Act. The expected benefits vanished as criminals, spurred by bootlegging profits, became rich, powerful, and violent. Prohibition was repealed in 1933. Careful consideration must be given to the possibility of induced changes when proposed changes are implemented. SD analyses rarely consider such consequences.

It is important to emphasize that SD problem solving for living systems is a science-aided art that is highly dependent on the creativity, experience, and good judgment of the analyst. Therefore, all of the knowledge and disciplines that specialize in developing human creativity and judgment are important contributors to SD’s effectiveness. Since so many different types of factors influence the patterns of more complex living systems, analysts who study such systems must have a wide diversity of well-developed skills, knowledge, and creativity to be successful. Since few people receive a formal education with such depth and diversity, successful SD analysts must be people with strong motivation and capability to teach themselves on a continuous, life-long basis. Every study a SD analyst performs is a major learning experience, no matter how many studies the analyst has performed in the past. The self-teaching capability is rarely recognized in the SD literature.

3.8 Planning for and Implementing Proposed Changes in the Real Loop Structure

Discovering possible, effective changes for existing feedback systems is difficult. However, actually changing real living systems in the ways specified by the proposals is much more difficult. Unless the subject system is very simple there will be several, perhaps many, changes to be made. In order to be effective, the changes may have to be made in a pre-specified order with important time constraints for accomplishing certain parts of the changes, and with proper coordination of the results of the changes as they are accomplished. Not only must the specified changes be made, but changes must be avoided for the relationships in the system that are not desired nor expected to be changed. In order for the changes to be made correctly, an implementation plan is needed. The plan will specify in considerable detail what is to be changed. It will say how it will be changed, who will change it, when it will be changed, and where it will be changed. It will describe how changes will be financed and staffed, what resources will be required, how they will be obtained, what training will be needed for the system participants and who, how, where, and when it will be provided. It will say what new technologies will be needed and how they will be provided. Even the training for the supervisors and trainers must be planned. The better the planning, the fewer the mistakes; but no planning can be perfect. Politicians may believe that all you have to do to change human behavior is to pass a law. But history teaches us that laws are often broken, sometimes flaunted, and seldom quickly accepted.

Of course, having a plan does not guarantee that it will be carried out in an effective, timely manner. Thus, the execution of the plan, the implementation of the changes in the real system, is different from and more difficult than developing the plan itself. Implementation is to a considerable extent a human or non-human-entity relations problem. Few people are simultaneously great analysts, teachers, persuaders, and role models. Who carries out the implementation is often as important as what is being changed. In the end, if the changes are not made properly, the benefits of the proposed changes and the meticulousness of the plan may be wasted.

3.9 Maintenance and Continued Evaluation of the Improved System

The implementation of changes in the system's feedback structure and in the participants' mindsets is not the end of a SD study. The details of the transition period response must be observed, evaluated and corrected as necessary. After the modified system is in operation as intended with improved patterns as desired, the analyst must continue to monitor the loop geometry and time patterns. No system structure remains effective forever. Parts of the system change, the environment changes, technology changes, objectives and personnel change, social and economic conditions change. One of the greatest problems is in maintaining the correct operation of the modified parts of the system. In day to day operations, modified decisions are supposed to be made in accordance with the feedback concepts on which the new system is based. These were created in the SD analyst's mind. Many decision-makers may not fully understand the complex feedback control paradigm that the analyst created. Even if the decision policies are represented in decision equations that a computer can calculate, exceptional situations will arise that require human judgments to modify the computations to keep the system's operations in accord with the paradigm. The decision-makers often cannot determine the correct modifications, so they may need help from the analyst. Sometimes it may even be difficult for the analyst to reconstruct the whole system paradigm so he/she can advise the decision-maker. The idea that the analyst is an objective consultant who is separate from the system, and is no longer needed after the changes are made, is not true. SD analysis should be continuous and unending as an integral part of the system, just as inspired system leadership, of which it is a part, must be.

4. Pattern Feedback Control

4.1 System Structure Change: A Higher-level Feedback Process

Ordinary feedback control involves closed sequences of causal influences in which values of cause variables at points in time influence the values of effect variables at that time or shortly after it.

Since the influences are arranged in loops, all of the variables have both cause and effect roles. Many cause/effect influences organized into many connected loops create the feedback structure of the feedback system. The operation through time of these cause/effect relationships arranged in loops that are coupled to each other produces time patterns that are combined in various ways to create the time histories of the system's variables. The value of a variable at a point in time is not independently determined for that variable at that time. The value of the variable at that time is the value of the combined patterns at that time. So the value of one variable at one time is the result of many variables interacting in many loops over long periods of past time. If the value of a variable at a point in time is undesirable, it cannot be changed directly. Undesirable time patterns themselves cannot be changed directly. The parts of the feedback structure that produce the undesirable patterns must be changed, so the system will produce a better time history. The indirect nature of effective control, which begins with the inability to control accumulation type variables directly, has existed since the beginning of time. It has only been in the last century that feedback control theory has identified these feedback relationships to permit explicit quantitative design and problem solving. While humans have designed simple feedback controlled devices for thousands of years without knowing what they were or how to analyze them, the development of modern mathematics has made it possible, explicitly and quantitatively, to design systems and to solve dynamic problems in complex feedback systems.

Ordinary feedback systems create changes in the values of variables based on the feedback of information or physical forces at a point in time. Thus, equations that represent causal relationships in such systems involve the effect variable at a point or over an infinitesimal interval of time (.K or .KL) on the left hand side of the equation; and a function of the cause variables at the previous point in time or over the previous interval of time (.K, .J, or .JK) on the right hand side. The computer program that is used to simulate such a system needs to retain only the immediately past values of the variables to calculate the new values as it steps through time.

In Pattern Feedback Control, in which the system structure (loop geometry or system equations) is changed, values of variables at a point in time are not fed back. Instead, a substantial number of values of one or more variables over a long interval of time, i.e. a time history, is fed back. [Actually, the time history is not automatically fed back, the analyst must intervene in the system to reconstruct the time history, unless the system was programmed in the past to record and save the past values.] From these whole time histories, the analyst or manager attempts to identify the characteristics of the time patterns that compose the time histories. This can be an extremely difficult pattern recognition problem; if there is substantial noise in the time history (especially if the frequency spectrum of the noise overlaps the signal frequencies); or if there are many patterns that are not functionally precise; or if the pattern-combining algorithm is complex; or if there are few data points in the time history. In order to represent this pattern recognition process, the computer would have to store and have available all or many past values of a variable, not just the most recent value. The pattern recognition algorithms whether mathematical or intuitive would also have to be programmed into the simulation program. Equations would not be written to find the present values of the variables as in ordinary FCT. Equations would be written to determine the types of patterns (functions such as sine waves, exponential increases, and damped oscillations) that make up the time histories. Then, the parameters of those patterns (the values of the periods and amplitudes of the sine waves, growth parameters and starting values of the exponentials, et cetera) would have to be determined for each variable of interest.

Other items that are fed back are observations of accumulations, flows, relationships, and operations; and answers by system participants to questions about the ways in which the system is operated and the ways that decisions are made. These also are not automatically fed back. The analyst must intervene in the system to observe or elicit them. Since the analyst only sees or hears what he/she looks for, or asks about, or accidentally stumbles upon, the dominant relationships can easily be missed. It is from these observations and answers that the analyst hypothesizes the dominant loop geometry. Here the "variable" of interest is not a single time value for a clearly defined entity, but the analyst's perception of the nonplanar map of the system's dominant loop geometry that existed during the period when the patterns in the time histories were created. Since the loop structure could have changed several times during the data period of the time histories, the analyst must not only determine what geometry is dominant at the time of the observations, but also what geometries were dominant throughout the data period. Obviously, the types of variables that are fed back in PFC are very different from the single values of variables at the present time that are fed back in ordinary feedback systems. *These unusual feedback entities are necessary because the patterns cause the problems and the loop geometry causes the patterns, so the dynamic problem has to be solved by understanding and then changing the loop geometry.*

After analysis, synthesis, and planning for implementation, the geometry of the real structure is changed, instead of changing the value of a variable. This difference between short-term value control and long-term pattern control is recognized quite clearly, but without its feedback control aspects, in military science. The destruction of the military forces and equipment of the enemy on the battlefield to win a short-term battle is called tactical warfare. The destruction of the enemy's financial and natural resources, his weapons research and manufacturing facilities, his transportation and communications facilities, and the will of the general population to support the war, all to achieve a long-term advantage in winning the war, is called strategic warfare. In the American Revolutionary War, the revolutionaries won few battles, but the strategic difficulties faced by the British in fighting a war an ocean away while fighting a war with France nearby, eventually were decisive. There are many important implications of the Pattern Feedback Control process and no mathematics exists for the analysis of PFC loops. Some of the properties of this new kind of feedback follow:

1) The "variables" that are fed back in PFC are different from those that are fed back in ordinary feedback systems. In PFC, data about whole time histories are fed back, not just single present values of variables. Sometimes, observations of operations and answers to questions are also fed back. These are the data inputs that the analyst must use to hypothesize the nature of the undesirable time patterns in the time histories and the feedback loops that cause these patterns.

2) PFC involves more creativity and greater impact on system performance than ordinary feedback control, therefore, it is less predictable and more important for system success. That is why a good system leader is so important; and, in large, real systems, is so highly rewarded.

3) The dynamics of the PFC process involve patterns of patterns, where the trends and oscillations of time pattern characteristics are the behaviors of interest.

4) The Pattern Feedback Control process is an integral part of human systems. Observation, analysis, and implementation of structure changes are not separate, independent, objective activities. Anyone in an organization may initiate organizational change either consciously or unconsciously. A SD analyst should not be a consultant, but a continuing improvement agent within the system. Observation often affects the system's behavior, even if there is no attempt to implement changes. The analyst cannot be objective and impartial; he/she is subjective, creative, and involved.

5) The time perspective and scope of the system are much longer and broader in PFC than in ordinary feedback control. The analyst or manager who is responsible for maintaining the effectiveness of a human system should extend his/her past time perspective back over a long

enough period of time to observe the longest period cycles of importance at least twice. Future time perspective should extend far enough into the future to visualize the transition period and the development of the desired patterns. Perhaps, it should extend far enough to foresee changes in technology, the environment, or the competition that will necessitate the synthesis of new structure changes to compensate appropriately for general changes in the world of the organization. The perceived breadth of the system must be extended to include all of the system’s parts that may affect the patterns significantly. The current advanced stage of globalization of technology, communications, the Internet, economic trade, tourism, investment, et cetera requires a very broad system perspective indeed. Today, there are few national economies that can be studied alone, in isolation from world currency, capital and economic interactions. There are few companies with stock publicly traded anywhere whose fortunes are solely determined by local forces. There are few families anywhere that do not use at least one product every day that was imported from another country.

6) PFC can be and is initiated and implemented by people and groups other than SD analysts. These change agents may not be as quantitative, theoretical, and systematic as SD analysts. Some may initiate structure changes with only pattern observations, particularly if their strategy involves replacing the leadership that is responsible for creating the structure (e.g., firing the old coach or president and hiring a new one). Some changes may happen accidentally (e.g., the president of a company may die).

7) In PFC, the subject system’s whole loop geometry is the major accumulation. It is similar to an ordinary accumulation, in that it can only be changed indirectly by controlling a flow of changes; so the pattern control process involves influencing the flow of loop changes. However, the loop geometry accumulation is a new kind of complex, time-varying, topological accumulation that does not have a single value to represent it. The geometry accumulation is in effect a transfer function in the Laplace transform sense, but the LT cannot be used because it is only defined for linear, time-invariant system equations. In most human systems, some of the system’s equations are nonlinear and the nature of PFC as a structure change process makes some of the system’s equations time-varying. These complicated, difficult properties of the loop structure accumulation will require a new kind of mathematics for its analysis that has not yet been created.

8) Several PFC loops may be in operation at the same time in a particular system. In fact, structure change activities on the part of one individual or group often stimulate others to initiate their own structure changes. The properties of such PFC competition may be very important in improving global-level living systems.

9) Time delays in PFC loops, particularly the waiting times required to measure the pattern characteristics, to accomplish the analysis, synthesis, and implementation; and to wait for the new patterns to appear may be longer than most delays in ordinary feedback systems. They will have a major impact on the success of PFC loops, especially when several PFC loops are competing for pattern control.

10) Analysis of the PFC process raises the SD art to its highest level of creativity and importance and imposes the greatest demand for technical skill on the analyst.

11) PFC loops may be more sensitive to instability (positive PFC loop reinforcement) than ordinary loops. Therefore, stability analysis for PFC loops is imperative, especially for global-level systems.

12) Structure modification typically has two parts: 1) changes in the highly aggregated feedback

control structure of a subject system for strategic control of the critical variables' patterns, and 2) changes in the details of accomplishing the aggregate control decisions. SD is appropriate for the former to set the aggregate values for important decisions. Other quantitative methods such as statistics, operations research, optimization, linear programming, et cetera, often can and should be used for the latter. In a SD study of an electronic components manufacturing system, one of the policy changes involved the production scheduling decision. The SD analysis provided an equation that specified the total number of components to be manufactured each week. Since there were 600 distinct catalog items for this product line, it was necessary to specify the number of components to be made for each catalog item. The sum of these individual item orders had to equal the weekly total production specified by the equation. To do this, the ordering history of each catalog item had to be statistically analyzed as the basis for optimal lot size calculations for each item and for the determination of current ordering priority for each item. Thus, the complete specification for the exact detail of the ordering decision required a coordinated analysis using SD, statistics, and optimization methods. Sometimes people assume that SD and other analytic methods are competitive or mutually exclusive, when, they really are complementary. Therefore, a good SD analyst must understand and use these other methods, if the aggregate policies that he/she develops are to be implemented effectively.

The complex, unfamiliar nature of Pattern Feedback Control loops greatly complicates the task of actually improving the real performance of living systems. Since most analysts end their involvement in system analyses with written reports before the implementation of changes even begins, they never experience the host of problems that can arise in the details of making the recommendations work in the real world. The separation of the system analysis from the control of and responsibility for the final real results greatly reduces the study's chance of success, especially in global living systems. It also reduces the chance that analysts will discover their analytical mistakes and will learn about the problems in making recommendations work in real systems. It is suggested that a great deal of research is needed in the area of Pattern Feedback Control.

4.2 A Final Complication: Human Beliefs, Conceptualizations. Visions, and Attitudes

The relationships between ordinary feedback control in living systems and the Pattern Feedback Control process is shown in symbols in Figure 2. It presents the physical and organizational aspects of the system's loop geometry that produce the time patterns for the important variables that have been selected for study and the PFC process that is designed to modify the geometry to change the time patterns. Figure 2 does not show the aspects of the individual and collective mindsets (beliefs, concepts, attitudes, knowledge, instincts, visions, objectives) of the system's participants (human and non-human) that created the original physical system and that support the system's continued existence and operation. Everything that exists in a physical or organizational form existed first in intangible conceptual (spiritual) form in the mind(s) of its living creator(s) and/or in the mind(s) of higher order entity(s). [Of the six billion humans living today, at least 80% demonstrate their belief that higher order creator entity(s) do exist through their membership in the religious organizations of the world's many faiths. In 1995, there were approximately 2 billion Christians, 1 b. Muslims, 0.8 b. Hindus, 0.3 b. Buddhists, 0.2 b. Chinese folk religious, and 0.7 other religious. Only 1 billion people were non-religious or atheists.]

In addition, once created, the system's loop structure must be maintained and operated on a continuing basis or it will deteriorate and eventually be replaced by new loops and/or new systems that more accurately reflect the collective mindset. Carl Jung's work in clarifying the nature of the collective unconscious is the best recent source of enlightenment for SD analysts who are facing this issue in their studies. The origins of subconscious or unconscious human motivation and the human awareness of powerful spiritual forces beyond human control can be traced back to the earliest cave paintings. Ancient cultic artifacts; later religious and spiritual texts, such as the Vedas, the Tanach (Hebrew Bible), and the Qur'an; and "myths" presented in the Epic of Gilgamesh and Homer's works demonstrate the universal human awareness of spiritual forces. These and many other spiritual traditions have led to the complex spirituality of today's civilized and primitive peoples.

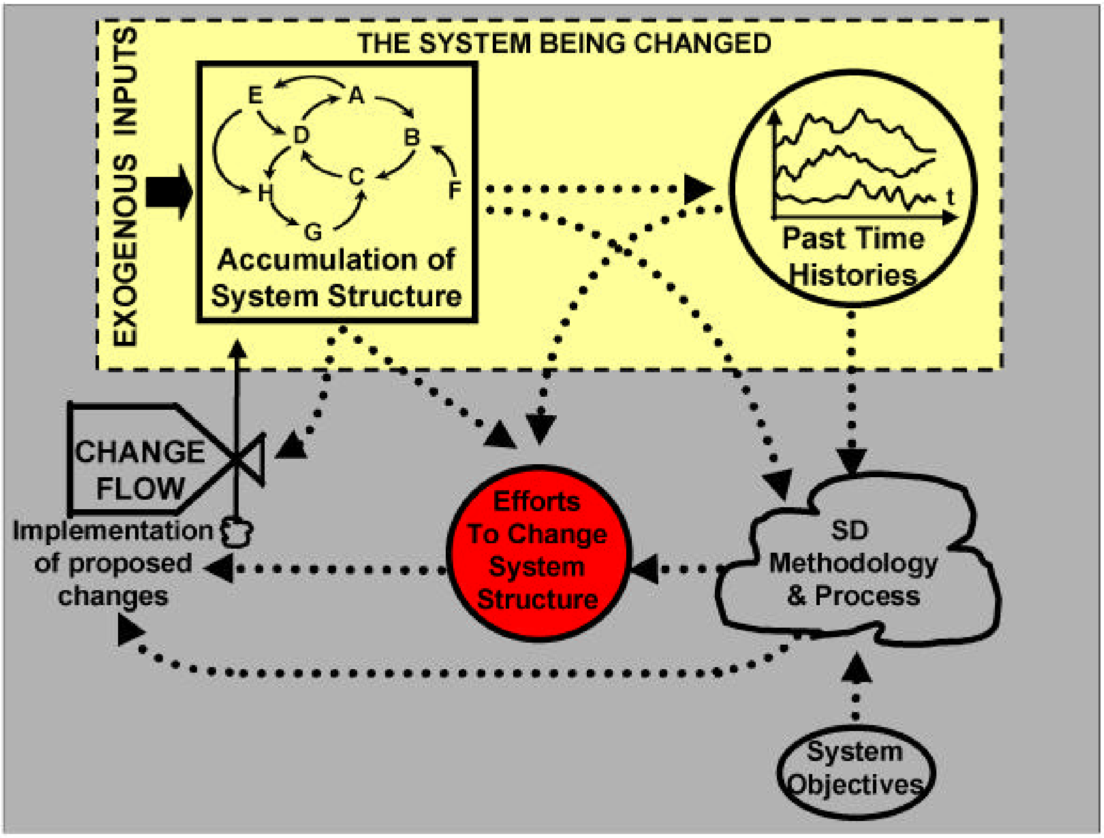

Figure 2. Pattern Feedback Control Process with SD Study as Change Agent

If the PFC process attempts to implement structure changes that are compatible with the system participants' mindsets, the changes are likely to be accepted and followed reasonably accurately. However, if the participants do not understand the proposed loop changes, or if they are incompatible with their mindsets; there may be great resistance to the changes and they may fail to be implemented. The prohibition disaster, as presented above, is a classic example of a change that was incompatible with the mindset of a majority of the system's participants. So prohibition not only failed; but its enactment precipitated great social trauma, some of which persists to this day.

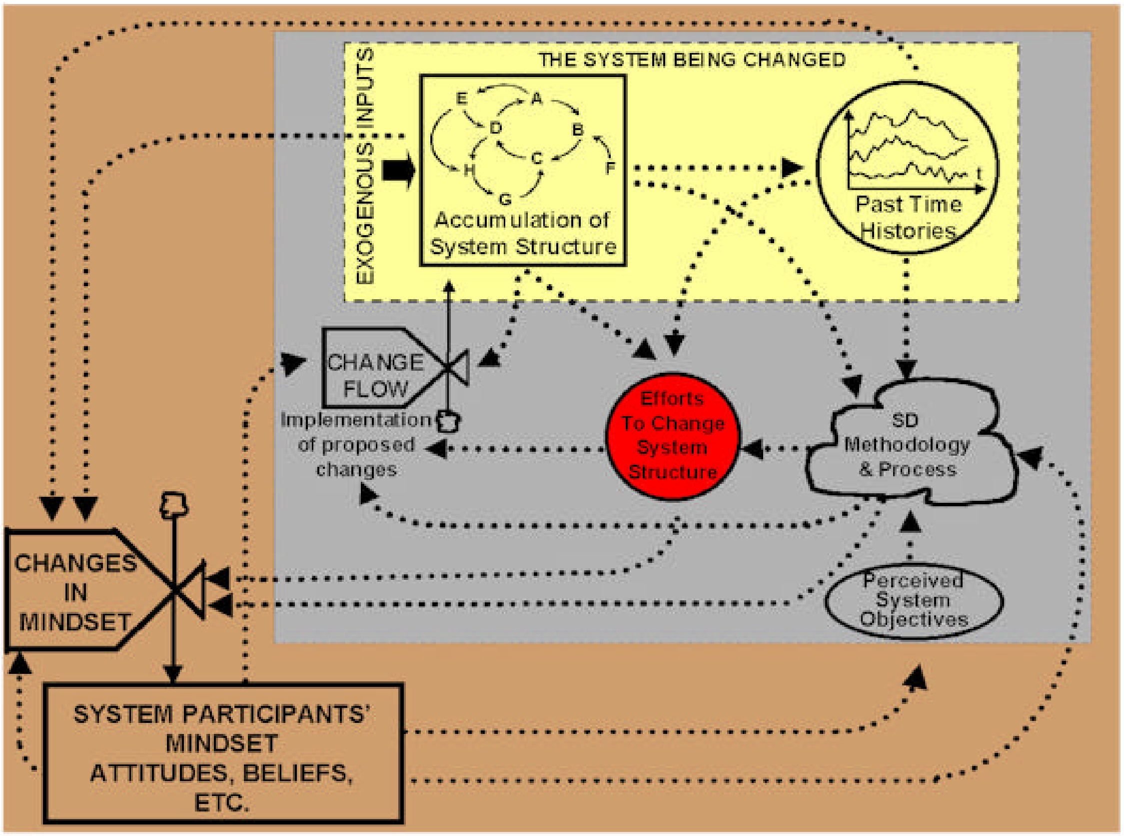

Figure 3. Figure 2 with the System's Collective Consciousness as Structure Support Added

The ultimate control by the collective mindset forces an analyst who seeks to change a system in ways that are not compatible with the system's collective mindset to do one of three things. Either the mindset must be changed, or the system's performance must be allowed to deteriorate to a point where the mindset looses its power, or the analyst must change the recommendations to conform to the mindset. The PFC process with its spiritual dimension is shown in Figure 3. The greatest problem for humanity today is the solution of the environmental crisis. It is confounded by major incompatibilities between humanity's prevailing mindsets and a mindset that would support a solution. The crisis is caused by the growth of world human consumption to such a great magnitude that the Earth's life support system can no longer sustain it. To save the environment, the growth of consumption must stop. However, almost every person, organization and government on Earth is committed to and dependent on this growth. Any proposed changes in the global system intended to stop this growth would be strongly resisted by the Earth's people and institutions. Therefore, the way to resolve this dilemma, if there is one, is not yet clear.

5. The Dynamics of Organizational Change

"The Dynamics of Organizational Change" may refer to several different kinds of time variations. The most obvious is the nature of the dynamic process loop structure that changes certain aspects of the way an organization operates (its feedback structure). There are many ways in which organizational structure change can arise. Some of them involve conscious attempts by individuals or groups to accomplish the changes. SD problem solving involves a conscious, sophisticated, analytical procedure for understanding the system's past undesirable time patterns and the system's feedback control structure, so the system's operations can be changed to solve the problems. SD analysts are trained to perform these tasks, though many have little experience in actually implementing changes in real operating relationships. Writing about making the changes is not the same as personally making the changes in the real system. It is remarkable how many unforeseen problems can arise when implementing proposed changes, even when considerable thought and planning have been invested in anticipating possible difficulties and taking precautions to avoid them. [It is like renovating an old house; you never know what crisis will appear next.] SD analysts are usually consultants, not line managers, so they seldom have the authority to make the changes themselves. That lowers the accuracy of the changes in the short-term. Since the line managers who supervise the changes and then manage the modified operations in the future usually do not fully understand the problem-solving paradigm, even more serious difficulties may arise in the long-term. It is difficult to be a SD consultant.

An organization's operating structure is usually changed by the organization's line managers. Such changes are usually consciously undertaken and, in large organizations, well planned. The extent of the analysis and planning and the kinds of data used to understand the dynamics of the system and the details of the old operating structure can vary considerably from one case to another. SD problem solving is one extreme on the analytical sophistication scale. The other extreme is the line manager who fires an influential manager (whose successor will create a change in structure) because he is a threat to line manager's position. In such a case, there is no dynamic problem to be solved from the organization's point of view, no gathering of time history or structural geometry data, and no planning for the implementation of the change except appointing a search committee to replace the deposed manager. In the latter case, the PFC loops are open because the line manager's decision is independent of organizational structure and performance, but changes in structure occur anyway. Thus, examples exist for all conditions along the analytical sophistication scale from the SD extreme to pure capriciousness. There are no data to support it, but I suspect that considering past time histories occurs more often than analyzing system structure. A careful analysis of the structure and the time patterns with the intent of relating them to the dynamic problem seldom happens. Probably the most common case is firing the coach or president when system performance is considered poor.

Organizational change can also refer to changes in the organization's time histories either during the transition period or after the new structure is operating as desired. An old SD principle is that time patterns often get worse before they get better after structure changes. If changes are made in very influential control decisions at a time when financial resources are depleted, the organization may not survive to experience the improvements of the new policies. Cash flow crises probably kill more organizations than any other problem, especially in this era of debt financing. The recent collapse in the technology stocks traded on NASDAQ, illustrates the vulnerability of companies to cash flow crises. That is why SD analysts should not forget to perform transition analyses to estimate how bad conditions will get and how long crises will last in their case studies. It is also important to recognize and analyze the PFC loops in each situation. From these loops, particularly those shown in Figure 3, an estimate can be made of how long it will take before the improved time patterns will appear. Also, problems can be anticipated that might arise to threaten a) the survival of the system, b) the effectiveness of the structure changes, c) the invariance of the parts of the system that were not changed, d) the effectiveness and sustainability of changes in collective mindset, and e) the success and longevity of the improved structure.

6. Conclusions

System Dynamics is, theoretically, the ultimate tool for those who seek to change organizational performance. SD philosophy and practice are based on a) the theory and practice of traditional mathematical feedback control; b) the disciplines that define, measure, and analyze all manner of living and human systems and relationships; and c) the methodology of SD dynamic problem solving. This SD improvement process is actually a part of a different kind of higher-level feedback process, Pattern Feedback Control. PFC has its origins in ordinary feedback control theory and topology. It suggests that to consistently, successfully, and demonstrably improve real systems, SD will have to develop and use the PFC principles necessary to improve its clients' performances; something SD analysts rarely do now. SD analysts must close the PFC feedback loops in real systems to achieve successful improvements; and the results must be well documented and published.

Since the collective mindset of living system participants creates and maintains the operating loop structure of the subject system, the origins and nature of the mental forces are more important than feedback control theory and the disciplines that study the physical variables; though these are still very important. Few people fully understand SD principles, especially the ones related to the dynamics of organizational change that arise from PFC. Major SD applications are so complex, are so dominated by technological changes, and are so dependent on these new concepts, that few have the experience, background, and creativity to carry an analysis through to a correctly implemented, improved, real system that is effectively operating as expected and as intended. In order to achieve its rightful share of influence in the professional and academic worlds, SD must perform successful implementations and demonstrate to the world the importance and validity of these achievements.

System dynamics has existed for more than 40 years, but it is not well known nor widely practiced. In principle, it alone addresses the most powerful forces that affect the long-term dynamic behavior of living systems. However, its methods do not recognize and utilize all of the important principles and procedures for successfully modifying real living systems to improve their time patterns. Few SD analysts are aware of the major difficulties inherent in each aspect of the SD methodology that must all be overcome successfully before improvements can actually be achieved. Fewer still have the knowledge, experience, creativity, patience, initiative, and courage to overcome all of the problems in a complex system analysis and implementation. Thus, it is imperative that all of these principles and skills, especially those related to mental forces, are developed and understood; and that many SD analyst-managers are trained quickly. It is an incredible challenge to perform the SD kind of open-heart surgery on a major company, industry, or country, while it is functioning at top speed in its accustomed way. But the ultimate challenge for any discipline that attempts to solve the dynamic problems of living systems is to resolve Earth's environment crisis without major social, economic, or military disasters before catastrophes in the life support system threaten human survival in this first century of the third millennium.

Bibliography

Aquinas, Saint Thomas (1265-1273). *Summa Theologica*. [Up to his time and beyond, Aquinas' work was the most successful and influential reconciliation of faith and intellect. SD also attempts to reconcile intellect (objective reason) and faith (spirit, emotion) in the creation and maintenance of human feedback systems by recognizing both as major contributors to human decision-making and creativity, the bases for the origination and operation of the systems SD studies.]

Bacon, Francis (1620). *Novum Organum*. [Bacon and Descartes are generally acknowledged to be the respective founders of the two philosophical principles, empiricism and rationalism, that together form the basis for the scientific aspects of system dynamics. In *Novum*, Bacon presents the principles of inductive logic in which theories of causation are induced from specific observations of conditions, states, or behavior arising from natural processes or designed experiments.]

Darwin, Charles (1859). *On the Origin of Species*. [Along with Alfred Wallace, Darwin conceptualized the theory of evolution through the operation of a process called “natural selection.” He postulated that many physical and mental characteristics of members of species were genetically inherited and that they changed through time to improve the survivability of species in their environments. This is an unconscious feedback process that produces species diversity and community stability in natural plant and animal communities.]

Descartes, Rene (1637). *Discourse on Method*. [In *Discourse*, Descartes presents the principles of deductive logic in which the causes of or reasons for specific observed results can be and should be deduced from theories arising from the intrinsic rationality of the experimenter’s mind. A third principle, reductionism, follows from the general hypothesis that the whole is equal to the sum of its parts. Descartes proposed the study of systems by studying the operations of their parts separately. However, for complex, nonlinear feedback systems, the whole is usually more, sometimes vastly more, than the sum of its parts. Therefore, SD rejects reductionism and practices whole system analysis, though decomposition to study parts in order to clarify the operation of the whole is sometimes done. In Cartesian rationalism, the mental reason, theory, or conceptualization is innate in the mind, not constructed from experience or training. It is an open-loop process. SD uses a procedure for system analysis in which induction and deduction form a closed-loop. From observations of a system’s relationships and time histories, a dynamic hypothesis which describes the feedback structure (the subset of dominant loops) that creates the important time patterns (the subset of dominant time patterns) is established in the analyst’s mind. This hypothesis arises partly from the nature of the observations (Bacon’s induction), partly from the logic of general feedback control theory (Descartes’ conscious rationality, but as arising from training in feedback theory, not pure natural reason which is not sophisticated in feedback logic); and partly from unconscious creativity (the origin of which is unknown, but it is far more than conscious logic). A mathematical model of this dynamic hypothesis is then used in a series of carefully designed simulation experiments to determine the correlation between the model’s response and historical real system time series data under similar conditions and between the model’s responses to many different structural arrangements and the responses anticipated by the analyst’s understanding of his/her mental model for similar arrangements. The effect of this procedure is to systematically modify the mathematical model and the analyst’s mental model until they both correlate “well enough” with each other and with the observations of the real system’s dominant structure and its dominant time patterns. Then the mental hypothesis and the mathematical model can be accepted as representing the “essence” of the real system’s feedback causality; and the model experiments can end. “Well enough” is both logically and creatively determined. It cannot be perfectly determined because both the model and the time patterns which the model attempts to explain are incomplete (subsets of the real structure and of the real time histories). It must be done this way because the mathematics cannot solve the system equations in closed-form and no synthesis algorithms exist to design the improved system. That is why the critical conclusions and decisions in both analysis and synthesis must come from the creative judgment of the analyst’s mind. Therefore, this whole exercise is designed to prepare the analyst’s mind to do well these extremely difficult tasks that cannot be done better any other way.]

Forrester, Jay W. (1961). *Industrial Dynamics*. Cambridge:The MIT Press. [The foundation of system dynamics, Forrester’s work presents the early system dynamics philosophy and examples of system dynamics analyses.]

Frazer, Sir James (1890). *The Golden Bough*. [This large (12 volumes), widely-read compilation of ancient myths, legends, religious rituals, folklore, and epics shows the breadth, importance, and similarities of the spiritual beliefs and practices of humans worldwide.]

Freud, Sigmund (1900). *The Interpretation of Dreams*. [This is Freud’s most important work on the unconscious forces that influence human behavior that he pioneered and on the philosophy of psychoanalysis.]

Gutierrez, Luis T. and Fey, Willard R. (1980). *Ecosystem Succession*. Cambridge:The MIT Press. [This is one of the earliest and the most extensive system dynamics analysis of a large-scale, aggregated, non-human living system (grassland biome). It illustrates the important variables that create most biomes' dynamic patterns, the limited positive feedback control process that regulates natural ecological systems, and the philosophy of studying non-human systems.]

Jung, Carl Gustav (1912, translated 1916). *Psychology of the Unconscious*. [This work is the classic exposition of the unconscious origins of individual and group behavior. Freud's work preceded Jung's, but was limited to the individual unconscious, primarily driven by sexual forces. SD is most effective in studying large human systems with the dominant controls at a high level of aggregation. There, the collective unconscious of a system's participants may be very important in developing the dynamic hypothesis and in designing the implementation plan.]

Machiavelli, Niccolo (1513 and 1521). *The Prince* and *On the Art of War*. [A pessimist about human nature, Machiavelli has been greatly misunderstood. In *The Prince*, he perceptively describes the workings of governments with realism, and counsels political leaders in attitudes and actions intended to preserve their position while supporting the governed in an aggressive, unprincipled era. *Prince* provided an early foundation for political science because it substituted perceptive observation and truthful understanding for the unrealistic Utopian theories that preceded it. In *Art of War*, Machiavelli presents the foundations of modern military tactics in a perceptive, realistic form that is applicable to many kinds of human conflict, not just military operations. System dynamics focuses only on the realistic, truthful aspects of human behavior as presented in the disciplines that were founded to study each aspect.]

Meadows, Dennis H., et all (1972). *The Limits to Growth*. New York:Universe Books. [The first mathematical model of the complete world system based on parameters derived from historical data, *Limits* illustrates the philosophy and methodology of SD in its most complex and most highly aggregated form.]

Richardson, George P. (1991). *Feedback Thought in Social Science and Systems Theory*. Philadelphia:University of Pennsylvania Press. [This is the definitive history of feedback concepts in systems theory and human system analysis.]

Smith, Adam (1776). *An Inquiry into the Nature and Causes of the Wealth of Nations*, New York:ed. Edwin Cannan. [The foundation of classical economics, Smith's work presents a theory of social order in which free markets, free trade, and the division of labor are conducive to economic prosperity (growth) through beneficial self-regulation by the "invisible hand" (feedback control loops). Our modern global economy closely resembles Smith's social order.]

Wallerstein, Immanuel (1999). *The End of the World as We Know It: Social Science for the Twenty-First Century*. Minneapolis:University of Minnesota. [This book describes the origins of the field of sociology, and elucidates the characteristics of our global socioeconomic system that will create the global environmental and sociopolitical crises that, in turn, will precipitate major changes in the philosophy and institutions of human society.]

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