INTELLECTUAL ROOTS AND PHILOSOPHY OF SYSTEM DYNAMICS

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Summary

Most SD work involves problem solving in existing living systems, whereas traditional engineering primarily creates designs for inanimate systems. SD uses the concepts and the mathematics (when possible) of mathematical feedback control theory (FBCT). Since the variables in living systems arise from human attitudes and activities as well as from non-human living entity's attributes, the general FBCT concepts must be applied to the practical realities of living entity variables and their closed-loop 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. Since problem solving for living systems is considerably more difficult than designing inanimate systems, SD philosophy and practice arise not only from FBCT, but also from all of the disciplines that attempt to understand particular aspects of living system behavior. 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 the causal relationships between variables in living systems. Since living systems function in an environment with dynamic nonliving factors, nonliving relationships (meteorology, geology, oceanography…) are often relevant. All of these fields may not be needed in any particular SD analysis; but, in general, 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 and use it properly. 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 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.

SD philosophy and practice includes the SD methodology for analyzing, synthesizing, and changing living feedback systems to achieve lasting, improved behavior patterns. The SD analysis methodology gathers data about real past and present loop structure and behavior patterns, analyzes the data, conceives changes in the loop structure that will produce better future patterns, and modifies the existing structure accordingly. Each of the activities and analyses is based on certain principles, philosophies, mathematical procedures, human behaviors, et cetera that are fundamental to successful SD practice.

This system improvement procedure is a feedback process different from the feedback control that science studies. We call it pattern feedback control (PFC). PFC has not previously been identified as a new kind of feedback control, and it has no appropriate mathematics for its analysis. In the PFC process, perceptions about past time patterns and 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 feedback geometry to the modified new real feedback geometry. After implementation of structure change and a transition period, the modified real geometry operates in the future to create new, improved patterns, thereby closing the pattern feedback loop. The old geometry is an accumulation of structured 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 feedback control accumulations, flows, and loops. It also has an important additional complication. 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 (conceptual and spiritual) issues, the collective mindset, are the basis for the creation and maintenance of the operating real structure. If the proposed modified geometry (the recommended improved system) is incompatible with the system's collective mindset, the mindset must be modified to be compatible before implementation of the changes, otherwise the implementation may be difficult or impossible to accomplish. The PFC considerations will determine the success of any system improvement process.

When used properly, SD can be a very effective discipline for solving long-term dynamic problems in living systems. It uses the most important characteristics of how the world works to create dynamic behavior. It often needs information from fields devoted to understanding the important characteristics of living systems. Its methodology for system improvement embodies a new kind of feedback control that is essential for effective problem solving. This article deals with the nature and origins of these three areas of fundamental understanding; feedback control theory, the disciplines that study living entities, and the aspects of the SD methodology that create pattern feedback control; that are the basis for the successful improvement of real living systems.

1. Feedback Control Theory

1.1 How the World Creates Feedback Loops

Two elementary types of essential variables, accumulations and flows (levels and rates), operate in the world. A nonessential third type, concepts (auxiliaries), is used for clarification and simulation purposes. Since the quantity of an accumulation reflects the present difference between the total historical flows in and out, a particular accumulation's quantity cannot be influenced by anything except what has flowed into and what has flowed out of it. Thus, the critical characteristic of an accumulation from a dynamic analysis perspective is that it can only be controlled (changed) by its flows. *It cannot be controlled directly*. The concept type of variable is used for such things as desired values, expected values, efficiencies, concepts, and variable delay times. However, the process that creates a variable's value determines the type of variable that it is. A price may be an accumulation or a concept depending on how it is determined. An electrical current is a flow in electrical interactions and an accumulation in magnetic processes. It may be quite difficult to identify the types for some variables in human systems.

In real living systems, the values of some accumulations must be maintained within tolerable ranges or the system will be at risk. If the value of an accumulation is "important" to people or organisms; consciously or unconsciously, they will try to control it. In order to control it, they must control one or more of its flows. The lack of direct accessibility to accumulation values combined with the requirement that the value of the accumulation be included in the flow control, forces the creation of feedback control loops.

The world works in this accumulation-flow-feedback-control way for all systems, no matter what units the variables have. In nonliving systems there may be no desired values, but feedback loops still create the dynamics. The trajectory of the earth's motion around the sun is an ellipse that 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). If a meteor struck the earth and deflected it into a new 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. The world has worked that way since the beginning of time, and it will work that way forever.

1.2 How Feedback Loop Structures Create Time Patterns

The inaccessibility of an 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 operating through time, given the magnitudes and delays of the individual causal influences, creates the time patterns (trends and oscillations) that are experienced by the system's variables. Therefore, the value of a variable in a feedback system at a point in time is the value of the time pattern at that time. It is not an independently created value for that variable at 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.

1.3 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, flows, and loops, understanding its operation becomes much more difficult. Then mathematics may be 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 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 modern explosion of technology for designing physical systems.

To represent mathematically the most elementary feedback interaction, two equations are needed. The first must represent the way the flows cause the accumulation to change. The second must represent the way the accumulation causes the flows 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. The second equation involves the use of algebra and, sometimes, logic functions. Algebra was invented before 1500 B.C.E. in Egypt, Sumer, India, and China; later, Greeks and Arabs improved it. Logic functions were developed recently. Until the 1600's, only a few people knew that an equation of the first type was needed.

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 and 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, all engineering universities require students to study it. 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 is exercised through information or forces that feed back 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 no more than 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 or 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.

In the early 20th century, the feedback control geometry of differential equations was explicitly recognized and the physical meanings of the LT and its complex frequency variable, s, were perceived. Separation of the system's contribution and contributions from 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 takes 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 obtain the LT of the output function. The ease of mathematical manipulation in the frequency domain ushered in the era of feedback control system analysis and design in the s-plane using LTs. 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 was achieving stability.

As the 20^{th} century progressed, discrete time functions were represented with difference equations (discrete time integral equations). Noise (random variations in the time functions of systems' inputs and outputs) was represented in the frequency domain, and methods of filtering and modulation were developed that could remove or reduce it. Auto-correlation and cross-correlation functions were developed to represent statistical characteristics of time functions. The LTs of correlation functions, called power density spectra, are used to design feedback systems with improved statistical behavior.

Two approaches to the algorithmic optimization of a system's performance were discovered in the 20^{th} century. The more commonly used type involves determining a time function to be added to or subtracted from the input time function to produce an "optimal" output time function. This type does not require changing the feedback structure of the system. The other type derives the transfer function for a compensation network that is added to the feedback structure of a system to obtain an "optimal" output time history.

The optimization methods provide optimization algorithms that take the system's equations and its objective function and derive the optimal solution. Unfortunately, both types of optimization 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 many real living systems' objective functions do not conform to the required criterion of minimum mean squared error between desired and actual output time functions. However, these methods work well in engineering systems. We could not have transported people to the moon and back without them.

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; so the emphasis in FBCT is on the deterministic aspects of behavior. Since stochastic processes exist, analyses of noise and of stochastic properties of systems are performed by writing causal equations for variables with noise and by analyzing stochastic system performance.

The mathematical principles and methods of FBCT 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 is the primary practical theme of modern mathematics and engineering. It is the universal analysis tool. SD is the logical heir of these powerful and universal principles and methods of science.

However, when the subject system contains living beings and the control functions arise from human attitudes and perceptions and the attributes of non-human living entities; the simple, quantitative application of FBCT, that is so successful in engineering systems design, is less effective. The aspects of living system operation that cause this degradation and the disciplines and new concepts that are required to retain effectiveness in human system problem solving are considered next.

2. Living System Disciplines

2.1 Living System Complications

Living systems are nonlinear and complex, 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. When the individual first-order accumulation equations in Laplace-transformed format are put in numerical-coefficient matrix format and solved for characteristics other than their time functions (e.g., stability, controllability, etc.), solutions may sometimes be obtained for higher-order systems, but not as high-order as often 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. FBCT is seldom used explicitly to design living systems with specific dynamic responses and stability criteria. In fact, living systems are often 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 or 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 considerable judgment in using FBCT principles to improve living systems. Thus, SD is a science-aided art, rather than an exact science.

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Bacon, Francis (1620). *Novum Organum*. [Bacon and Descartes are accepted by many to be the respective founders of the two philosophical principles, empiricism and rationalism, that together form much of 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.]

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Biographical sketch

Professor Willard R. Fey, born 1935, was one of the original members of the Industrial Dynamics Group that developed the System Dynamics (SD) methodology at the Massachusetts Institute of Technology (MIT). He received his academic education at MIT in electrical engineering, industrial management, systems theory, economics, psychology, and social science. While teaching at MIT, he directed the first industrial dynamics educational program, for which he received the 1966 Everett Moore Baker Award. In 1969, he brought the new field of System Dynamics to the Georgia Institute of Technology, where he has taught for 30 years. As a consultant, he has conducted SD studies of real human systems (military, higher education, criminal justice, ecological, and business) which have resulted in improved policies and procedures. He retired from teaching in 1999 to devote time to environmental research. He is currently the CEO of Ecocosm Dynamics, Ltd. (see www.EcocosmDynamics.org), a non-profit corporation that is the administrative home for this research.