Tutorials in Motor Behavior
G.E. Stelmach and J. Requin (eds.)

297

1

ON THE CONCEPT OF COORDINATIVE STRUCTURES AS DISSIPATIVE STRUCTURES: I. THEORETICAL LINES OF CONVERGENCE*

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A model construct for coordination and control is pursued according to three related guidelines: (1) that it directly address Bernstein's problem of how to explain the regulation of the many biokinematic degrees of freedom with minimal recourse to an "intelligent regulator"; (2) that it be miserly on the number of explanatory principles, sui generis; and (3) that it be consistent with established strictures of non-equilibrium thermodynamics, that is, physical principles that inform biological design. Argument is given that a group of muscles constrained to act as a unit, a coordinative structure, is a member of the class of thermodynamic engines qua dissipative structures and that this membership gives a principled basis for understanding the characteristics of coordination and control.

1. Introduction

What should we take as the model construct by which to characterize the control and coordination of movement? Several candidates have presented themselves over the years: The linear chaining of reflexes or, more generally, the concatenation of stimulus-response connections; the musical-score metaphor of the past century transformed into the contemporary concept of central program; and the feedback, error-correcting mechanism fundamental to cybernetics and its allied disciplines. Our purpose in this essay (and its companion which follows) is to promote a lesser known candidate: We will give serious consideration to the idea that a group of muscles constrained to act as a unit is a member of the class of dissipative structures characterized by limit cycle oscillation and it is by virtue of this membership that the control and coordination of movement has the character that it has. We intend to show that this model construct of dissipative structure, in comparison to other candidate constructs, is more closely consonant with contemporary thought in biology, is a more principled basis for understanding the whys and wherefores of control and coordination and is more able to accommodate criterial findings about speech production and about the movement of limbs singly and in combination.

2. Bernstein's Problem

The deepening of inquiry over the past two decades into processes that mark animals as epistemic agents (as compared to animals considered only as biological or physical entities) has brought into sharp focus two closely related problems which, for historical import, can be labeled Hume's problem and Bernstein's problem.

An often-voiced and generally agreed upon argument is that there cannot be a successful theory of psychology (or of physiology for that matter) which does not include at its core the notion of representation. Representation, however, implies a user--an agent with goals, interests and comprehension. That is, representation implies some entity--an animal-analogue--very much like the entity--an animal--that we are attempting to explain through the mechanism of representation. The infinite regress so enjoined undercuts the possibility of a successful psychology or physiology. We can summarize the argument as follows: Viable theories of psychology and physiology require the concept of representation, but representation implies an animal-analogue which, in turn, implies an infinite regress; therefore, there can be no viable theories of psychology or physiology (see Dennett, 1978).

There are two responses to this dilemma. One response is to seek a better understanding of the causal and logical support for psychological and physiological phenomena, one that renders representation superfluous (see Gibson, 1979; Kugler, Kelso & Turvey, in press: Shaw and Turvey, in press; Shaw, Turvey & Mace, in press; Turvey & Shaw, 1979). The other and more frequent response is to pursue the possibility of self-understanding representations so that no complete animal-analogue appears in the system. The latter pursuit defines the problem of the seventeenth-century philosopher David Hume who sought to fashion a psychology on the notion of the entrainment of ideas through the laws of association. Hume wanted ideas to think for themselves, as it were.

Bernstein's problem is very much like Hume's problem--the difference is simply one of emphasis. Whereas Hume focused on phenomena characteristically referred to as mental, Bernstein (1967) focused on movement. His problem may be stated as follows: How can the very many degrees of freedom of the body be regulated in the course of activity by a minimally intelligent executive intervening minimally? Or, put differently, how can the degrees of freedom be dissipated systematically at minimal computational cost? Whenever we are trying to understand a complex system we are prone to attribute some portion, often large, of its intelligent activity to the intelligence of a controller. That is to say, as theorists we take out a loan on intelligence, principally in the currency of computational know-how, for the executive component of the system--a loan that must eventually be repaid if the system is to be fully understood (Dennett, 1971). Executive intelligence *qua* computational sophistication cannot be an unanalyzable residual.

Bernstein's problem can be more readily appreciated by recasting it as a list of principles to be followed for the problem's resolution: (a) keep the number of free variables to be individually regulated at a minimum; (b) keep the number of executive instructions per unit time at a minimum; (c) keep the number of executive decisions about what kind of instruction or command to issue at a minimum; (d) keep the number of executive decisions about when to issue an instruction or command at a minimum. The list is far from exhaustive but it suffices for the present purpose. For theorists sensitive to Bernstein's problem, the task is to identify a style of organization that gives adequate realization to these principles and their cognates (Boylls, 1975; Fowler, 1977; Greene, 1972, 1975, 1978; Gurfinkel et al., 1971; Tomović & Bellman, 1970; Tsetlin, 1973; Turvey, 1977; Turvey, Shaw & Mace, 1978).

But there is one terribly important aspect of Bernstein's problem that we can not fail to address if we are to fully appreciate the style of organization that is being sought. It has to do with the definition of "costliness." Bernstein's problem is so stated as to emphasize the algorithmic or computational bases for the controlled dissipation of the body's degrees of freedom. As such the problem could be addressed (although there are strong hints that Bernstein himself did not believe it should) in formal terms, of mathematics and logic, without concern for the actual dynamics of the physico-chemical structure that must embody the solution.

Axiomatically, algorithms as effective procedures must be embodied and one might be satisfied with the claim that the "embodiment" is captured sufficiently by the particulars that define the universal Turing machine. There is a very strong inclination in the contemporary science of epistemic agents to define the costliness of a computation in strictly Turing machine terms--to worry about storage demands, speed, reliability and the like. Indeed one might use such cost variables to determine the tractability of algorithms. Thus, Stockmeyer and Chandra (1979) show that certain computational problems that are algorithmically solvable in principle would require a computer as large as the universe, composed of parts as small as the proton, running for as long as the age of the universe. Needless to say, such algorithms are deemed intractable.

But very little thought is required to appreciate that abstract automata formally equivalent to the Turing machine do not satisfy the natural constraints that must be met by any actual, evolved epistemic agent. (A Turing machine, it must be remembered, is a mathematical not a physical object.) The cost variables imposed on organisms by the laws of physics and biology are quite different from those formally placed on the workings of abstract automata: They are variables that bear no essential relation to the intuitive concept of algorithm for they are, in large part, variables relating to the exchange of energy and matter between an organism and its surroundings (Shaw & McIntyre, 1974).

It should be argued, therefore, that neither the "costliness" referred to in Bernstein's problem nor the solution to the problem can be conceptualized in a purely mathematical or logical vocabulary. Imperatively, the organization of control and coordination that we seek must include physical (read, dynamical) concerns as intrinsic to its style. To include them secondarily, perhaps as adjunct adjustments to purely formal constraints on algorithms, will not be sufficient; for it would assume too arbitrary a relation between an algorithm and the device by which it is executed (Shaw & McIntyre, 1974). Indeed, as the physical basis for control and coordination is better understood, algorithms as explicit logics may no longer be necessary for the resolution of Bernstein's problem.

3. The Primacy of Dynamics

It is a truism that biological processes exhibit order and form but how should this truism be understood? A time-honored approach is well expressed in the analogy drawn by Descartes between the body and mechanical gadgets in which orderly events follow from the careful arrangement of rigid parts such as levers, weights and wheels. On this machine analogy Descartes sought to derive the orderly activity of the nervous system from the anatomical arrangements of the body. Continuous with Descartes' machine conception--as it has commonly been called (e.g. Kohlers, 1968; von Bertalanffy, 1973)--are two later-day developments of considerable significance to students of movement, the feedback control systems of cybernetics (where control is based upon preestablished arrangements among components) and their close relatives, the algorithmic machines of Artificial Intelligence (where control is based upon preestablished ordered arrangements of specific instructions).

In opposition to the machine conception is the understanding that it is tendencies in dynamics--the free interplay of forces and mutual influences among components tending toward equilibrium or steady states--that are primarily responsible for the order of biological processes. Beautiful examples abound of the form induced by dynamic principles (Thompson, 1917; 1942; Stevens, 1974). For example, wherever spherical-like bodies of uniform size with soft or deformable walls are packed together (so that actual physical contact occurs at the boundary walls) they settle into a hexagonal pattern (such as a honeycomb), a pattern in which surface contact is least and potential energy is minimal. In such hexagonal tessellation, where boundaries or interfaces are minimized, three-way 120 degree joints occur. But three-way joints arise not only in conditions of close packing but under conditions of surface tension as with soap bubbles, cracking as occurs with elastic surfaces such as mud, wrinkling as occurs with fruits when they dehydrate and expansion as occurs when buns in close proximity are baked together in the oven. Common to all of these sources that produce the same pattern is the principle noted, namely, minimum surfaces or more properly the minimization of work or energy. It is important to note that the specific means by which the three-way, 120 degree joint pattern or form is brought into being is not as significant as how the constituent parts that become patterned relate among themselves. Put simply, if the parts are free to vary and find equilibrium, then they will arrange themselves in a configuration of minimum free energy.

The contrast between the machine conception and the dynamic conception of biological form and order is far from trivial. Clearly, the questions emphasized by a student of natural systems and the investigatory procedures adopted are very much influenced by which of the two conceptions are adhered to. It is true that the machine conception dominates the interpretation of biological and physiological processes. There are, however, very good reasons for believing that its application is often ill-motivated and premature. The possibility that the phenomenon to be explained is a phenomenon primarily owing to dynamics is often not explored or explored only superficially. In (perhaps larger) part the favoritism shown the machine conception, particularly in contemporary science, is due to the seductive fact that processes can be readily described in formal and quasi-formal languages, languages that are consonant with the machine conception. In (perhaps lesser) part, the favoritism shown the machine conception is due to the fact that dynamics traditionally has been preoccupied with continuous motions in spaces evenly populated with phase points (that is, with linear, conservative systems) whereas the problems of biology are expressed as discontinuities in spaces unevenly populated with preferred stabilities (that is, the problems of non-linear, non-conservative systems). The extension of dynamics into the latter domain has been slow but it is gaining in impetus (see below and, for example, Eigen, 1971; Katchalsky & Curran, 1967; Morowitz, 1978; Onsager, 1931; Prigogine & Nicolis, 1971; Soodak & Iberall, 1978).

The allure of the machine conception is especially evident in debates on the role of DNA where a very popular conception is DNA as a program, a set of instructions, which order the epigenetic processes in a particular fashion. But two lines of argument--one that questions the relevancy of the problem conceptualization of DNA and one that questions its tract-ability--show that the allure of this program interpretation in particular and of machine-conception interpretations in general leads to convenient and easily imaged models of process but it does not, necessarily, lead to an understanding of process.

The following in paraphrase is an argument of Goodwin's (1970). The piv-otal points in the epigenetic process are those at which the cell, faced with several reasonable ways to differentiate, must select one. Pre-sumably, on the program notion, at such pivotal points the cell follows a sub-routine which identifies what to do if certain conditions hold. On this notion, therefore, the cell can be construed as computing its own state, examining the DNA program for what it should do next, and then changing state accordingly.

In actuality what goes on in a cell looks quite unlike the process just described. The state transitions that occur appear to arise from the mutual relations among the constituents that define the state of the cell. Goodwin (1970) describes it this way: Suppose that through the catalytic operation of enzyme E_1 two precursor metabolite molecules U and V give rise to a particular metabolite Y. And that through the catalytic opera-tion of enzyme E_2, precursors V and W give rise to metabolite Z. If U, V and E_1 are available in sufficient amounts but either W or E_2 is absent, then Y is formed; if, on the other hand, V, W and E_2 are present simul-taneously in sufficient amounts and either V or E_1 is absent then Z is formed. In this description there is no computation of cell state, no referring to DNA for instructions and no change of state based on instruc-tions. DNA does contribute significantly to epigenesis but in more modest and cooperative (rather than imperative) ways than expressed in the program conception; for example, it can be argued that it is partially responsible for the current state of the cell and that it participates with fellow cellular constitutents in determining the prior rate of synthesis of enzymes and other macromolecules.

Our second argument is from Gould (1970) and Rudwick (1964). The synthe-tic theory of evolution gives more than lip-service to the relation of form and function but it tends to approach form through concepts that are non-morphological such as gene-pool and genetical fitness (Rudwick, 1964). Moreover, the synthetic theory coupled with the machine conception invites one to think in terms of programs as responsible for form, that is to suppose, in the extreme, that each aspect of a complex form is the direct product of an individual genetic instruction. Such a proposal runs into the problem of degrees of freedom as is well recognized by Gould (1970) who, in reference to the form of sea urchins (echinoids) believes it "inconceivable" that each of several hundred echinoid plates, crinoid columnals and radular teeth could be the product of independent genetic commands. Resolution to the degrees of freedom problem in this context is sought in the direction promoted most notably by D'arcy Thompson (1917/

1942) which is to adhere to a strategy which recognizes that physical forces directly influence form and that intricate final products might be fashioned on the basis of relatively simple constraints. Thompson (1917/1942) was of the impression that many aspects of form, even as manifest in advanced species, are the direct consequence of physical forces--configured according to an underlying geometry of stable arrangements--acting on pliable material. A "curtain" metaphor cited by Gould (1970) is illuminating: Intricate patterns of folds follow from specifying a few points of suspension.

Those who follow D'Arcy Thompson's thesis in principle, if not in detail, seek to identify either gradients (see Gould & Garwood, 1969 for a review) or a minimal number of rules (e.g. Raup, 1968; Rudwick, 1968), which in the context of freely operating forces will yield complex forms. The gradient approach is nicely captured in an example from Stevens (1976): If a circular slab of clay is depressed more at its periphery than at its center so that it grows faster at its periphery it will form a shallow shell-like structure with an undulating periphery; if depressed more at its center than at its periphery so that it grows faster at its center, it will form a bowl-like structure with a uniform periphery. And with reference to the "rules" perspective, Rudwick (1968) has shown that the odd-looking dorsal valve of the oldhaminid brachiopod (a shelled marine species popularly known as "lamp shells") can be generated by simply following the rules: "Keep a minimum distance from other lobes" and "bud a new lobe when the previous one reaches a limiting length related to the shell edge."

While the "gradient" and "rules" perspectives look suspect in the face of developments in qualitative and non-equilibrium dynamics (see below) the thrust of the argument is clear: Biological form is largely due to a free interplay of forces and mutual influences among components and if one wished to persevere with the conception of DNA as program then this argument suggests that the instructions in the program will be few in number and their content relatively simple. But we have already seen, in the preceding argument of Goodwin's (1970), that DNA is understood more properly as constraining--not instructing--the epigenetic process. It is a common characteristic (though, perhaps, not a necessary one) of the machine conception that responsibility for the manifest order of a biological or physiological process be ascribed to a single entity. Thus, on this machine conception, the question of why the state transitions in the phenotype are ordered as they are is answered by saying that it is because the instructions in the DNA are ordered as they are. However, with the embracing of biology by dynamics and the appreciation for DNA as a constraint, it becomes more apparent that the conditions for a biological process are not to be found invested in any single part of any special subset of parts but in the total organization. As Weiss (1961) and Goodwin (1970) would put it: The question of "what controls or coordinates?" a biological process should be answered with "the whole" rather than "the gene."

The tendency to explain a phenomenon (say, state transitions in the epigenetic process) by investing the phenomenon in an independent device (say, the sequence of instructions in the DNA program) is in keeping with the style of scientific inquiry that has been dubbed "self-actional" by Dewey and Bentley (1949). The extreme consequence of this style of inquiry is a semantic regress (Shaw & Bransford, 1977)--each distinguishable phenomenon has an independent device as its source. The main general consequence is that many phenomena are read as sui generis, that is, they are conceived as unique and fundamental and not explainable through an appeal to other principles. But as anticipated above a very different style of inquiry, dubbed transactional by Dewey and Bentley (1949) and coalitional, on elaboration, by Shaw and Turvey (in press), is consonant with the approach taken when a dynamic rather than a machine stance is adopted. Roughly, this style of inquiry looks at the system in full, emphasizes the mutuality of its "components," and tries to understand phenomena as system properties.

The claim on which we are converging, ideally, is this: That the order in biological and physiological processes is primarily owing to dynamics and that the constraints that arise, both anatomical and functional, serve only to channel and guide dynamics; it is not that actions are caused by constraints it is, rather, that some actions are excluded by them.

4. Constraints Rather Than Instructions

The gist of the foregoing can be expressed differently in a way that is more suited to the purpose of the present section. A formal system account of a physical system process (qua biological, physiological or psychological) necessarily requires discrete, serial operations and an explicit representation of every aspect of the process, both frozen and fluid. (Of course, a sequence of formalizations ordered in abstraction can be assumed so that all aspects of the process are not made explicit at one stage of description but are explicated over a succession of stages). By way of contrast, in an actual physical system the operations are mainly those of parallel and coordinated dynamics and many (if not most) changes need no explicit description since they are taken care of by the dynamical laws involving real space, time and energy. To paraphrase Pattee (1977), it is in the nature of real systems as opposed to formal systems that they are necessarily special purpose instantiations of logical operations which depend on a tacit "measurement" or "computations" process that does not have a detailed description anywhere--within or without the system.

Our intent here is to put into perspective the machine conception of control-cum-coordination as owing to fixed or relatively fixed instructional arrangements. In so doing we will highlight the contrast--touched upon above--between constraints and programs, or synonymously, between what might be termed declarative languages and imperative languages (Steele & Sussman, 1978).

The coalitional style of inquiry advocated by Shaw and Turvey (in press) claims that any naturally evolved system is comprised of two logically dependent components, the operational component (say, an organism) and its context of constraint (say, the econiche), and that any explication of systemic phenomena must be coordinated over four, mutually constrained and closed, grains of analysis in the sense that no grain and neither component is disproportionately accredited with responsibility for the phenomenon. Crudely, the grains (from higher to lower) are the basis grain, consisting of the dimensions or variables over which the system is defined; the relation grain, consisting of the relations among the variables; the order grain, consisting of the orderings that the variables take; and the value grain, consisting of the actual values that the variables assume. Whenever explanation is not inclusive of all four grains and not respectful of the mutualities among them, then the grain on which explanation primarily rests tends to burgeon in the detail and in the semantic richness required of its predicates. In particular, to fixate on a lower grain such as the order grain is to encourage more explanatory principles sui generis at the value grain than are scientifically desirable [This reiterates in different form a major point of the preceding section; for a more elaborate discussion see Dewey & Bentley (1949) and Shaw & Turvey (in press)].

We can now be more precise in our characterization of the formal machine conception of order and form in biology: It emphasizes the order-grain to the virtual exclusion of the grains above it. This is similarly true of the control theory that is often applied to matters of biology. It assumes a value (with sui generis status) that defines a desired state of affairs and then specifies how that value is achieved through an ordering of commands. In the words of Yates, Marsh and Iberall (1973), modern control theory gives undue emphasis to the communication or small signal aspects and ignores the "plant processes"--the high-power,energy converting machinery. The same criticism has been voiced, more particularly, for popular accounts of hunger control (Friedman and Stricker, 1976), and thermoregulation (e.g. Werner, 1977).

It is not a matter of happenstance that the machine conception of order and form in biology is fixated at the order grain. Consonant with the formal system approach referred to above, the currently popular programming languages are designed for expressing algorithms--that is to say, they are languages of unidirectional computation in which the flow of information through the network is explicitly organized. Programming languages with this characteristic may be labeled "imperative" languages (Steele & Sussman, 1978). An imperative language, it seems to us, informs an interpretation of control that is:(i) logically deep in von Neumann's (1959) sense of many formal mediating steps; (ii) separate from that which is controlled. (Thus, in computers the "how" of computation is separate from that which performs the computation; in control theory, the command-algorithm is separate from the power flux that it modulates; in the neurophysiology of movement, the central nervous system as controller is held conceptually separate from the skeletomuscular apparatus that performs the movement); (iii) conceptually indistinct from coordination in that to explicitly organize the ordering of variables is to make "control" self-sufficient and "coordination" redundant.

We began this section by remarking on the fact that in real physical systems as contrasted with formal systems, explicit description of most of the changes that transpire would be superfluous given the contribution of dynamics. This fact, in and of itself, undercuts the relevance of imperative languages for systemic phenomena. In addition we registered our misgivings with explaining systemic phenomena at a single and lower grain of analysis; not surprisingly, therefore, in our eyes any explanation fixated at the order grain of analysis must be suspect. There are two minimal requirements for moving in the direction of a more adequate account of systemic phenomena--include a dynamic vocabulary and, relatedly, extend explanation to higher grains of analysis. The inclusion of the vocabulary of equations of constraint and the concommitant extension to the relation-grain of analysis reduces the detail and changes the semantic content of the order grain. To anticipate, what emerges is a concept of control that is: (i) logically less deep; (ii) less obviously segregated from that which is controlled; and (iii) conceptually distinguishable from coordination.

5. Equations of Constraint

Consider a system of m independent dimensions. To define the position of any one element within the system would require m coordinates; and if the system were composed of n elements then a total of mn coordinates would be needed to describe the system. The system would be said to have mn degrees of freedom. If relations are now defined over the dimensions so that the position of any one individual element must respect the positions of other elements, then the number of coordinates needed to describe the system of elements would be reduced. These relations--termed equations of constraint--reduce the degrees of freedom of a system according to the general rule mn-c where c is the number of such equations.

How should equations of constraint be interpreted? The nature and origin of constraints in biology are deep problems that only recently have been carefully articulated (see Pattee, 1970, 1971, 1973, 1977). A full treatment of these problems cannot be given here but some important insights can be distilled. As conventionally distinguished there are two types of constraint--(relatively) time independent and (relatively) time dependent. Pipes through which water flows exemplify the first type of constraint--pipes permanently eliminate the motion of water perpendicular to the direction of flow. The second type, the time dependent, is the more interesting. Where an entity has the option of many alternative configurations or trajectories--such as the cell in differentiating--then we speak of a time-dependent, non-holonomic constraint that effectively selects one trajectory from among the virtual trajectories.

A constraint must have some distinguishable physical embodiment which means that it is at one and the same time obedient to fundamental dynamical laws and a constraint on them. If the degrees of freedom of the physical embodiment of a constraint were evaluated in microscopic detail they would be seen to follow the same deterministic dynamical laws as the degrees of freedom that the constraint is said to be selectively influencing. This line of argument leads to an important understanding about constraints: Constraints are distinct from the degrees of freedom they modulate <u>only in the sense</u> that they are <u>alternative descriptions</u> of those degrees of freedom. This, in turn, leads to a further important understanding: If the alternative description is to be distinct then it cannot be redundant, that is, it cannot be simply an equivalent description of the dynamic details; and since it cannot be, most obviously, a more detailed description, it mustbe a <u>less</u> detailed description. For Pattee (e.g., 1973) the usefulness of a constraint is that it capitalizes on the dynamical context without including a description of that context. In the very simplicity of alternative descriptions resides their potential for selectively manipulating complex dynamics. Thus--returning to DNA--as an alternative description DNA is sparse in detail compared to the detail of the dynamics of epigenesis. DNA is "mute" on the tens-of-thousands of interacting degrees of freedom that are involved in the structuring of amino acids and their manner of folding and operating as a rate-controlling enzyme (Pattee, 1977).

How do constraints arise spontaneously? It is useful to distinguish two forms of this question. In one form we ask how definite structures or regularities arise in physical systems that are initially homogeneous. In the other form we ask how it is possible for new dynamical restraints to originate in a physical system (at any scale) when the system's present state variables and dynamical equations completely determine the system's future state variables. A response to either form of the question must rest with an appreciation of the general nature of nonequilibrium systems.

6. Open Systems and Scaling Effects

Classical, equilibrium-oriented thermodynamics predicts that in isolated closed systems (that is, systems which exchange neither energy nor matter with their surroundings) things will run down to a state of maximum disorder, zero information, and loss of the ability to do work (cf. Bridgeman, 1941). This state is entropic equilibrium, and once in this state nothing new can emerge as long as the system remains isolated and closed. At this state the thermodynamic analysis is complete. The reversible quality of these systems is evident in the fact that if a perturbation occurs to the system at this state, the system responds by going through a succession of states, all of which are at entropic equilibrium. In short, the entire event occurs in a state space in which all points in the space are homogeneous with respect to entropic equilibrium. Each point in the space may be said to exhibit terminal point-stability or statically-stable stability. The concept of reversibility is reflected by the fact that there are no preferred points in the entropic state space: states may reverse themselves and still maintain entropic equilibrium. While some real events (such as very slow processes in the macroworld) are rather well described by classical equilibrium thermodynamics, most interesting events regarding living system are not among them.

An open system is markedly distinct from isolated closed systems in that it need not tend toward a state of thermodynamic equilibrium but more generally tends toward a steady state displaced from equilibrium (meaning that it has potential energy) that is maintained by a continual flow of free energy and matter into and out of the operational component of the system. Our reason for the tentative wording ("need not," "generally tends toward") in the preceding is to underscore the important fact that being an open system is not of itself sufficient to guarantee the critical property of biological systems that we are trying to understand, namely, the increasing order (lowering of entropy) or the appearance of new regularities (equations of constraint). A small temperature or concentration difference maintained across the operational component of an open system renders the system only slightly out of equilibrium and its tendency is to move as close as possible to maximum entropy, that is, away from structuralization. It is only when an open system is driven far from equilibrium that the spontaneous appearance of new structure and new organization becomes possible; a possibility that is realized if one further requirement is met--that nonlinearities be manifest in the relations among system components (Haken, 1977; Prigogine & Nicolis, 1971).

The emergence of (new) structure follows a set pattern. When the flux of energy and matter across the boundaries of the operational component of a system is low, the component is stable. However, when the flux is high and in excess of a critical value, the previous stability gives way to instability. Some of the fluctuations that were damped at the lower flux are amplified at the higher flux and carry or "enslave" the component as a whole to determine a <u>new</u> stability (Haken, 1977; Prigogine & Nicolis, 1971; Prigogine, Nicolis & Babloyantz, 1972). There are several fashionable examples of instability prefatory to a new structure or organization.

The Bénard or convection instability is manifest in a situation in which a fluid layer is heated from below and kept as a fixed temperature above so as to create a temperature gradient in opposition to the effects of gravitational force. At small values of this gradient heat is transported from lower to upper regions by conduction and macroscopic motion is absent. Random thermal motions of the molecules and a damping of convection currents characterize the state of the fluid. However, when the gradient exceeds a critical value a convective, macroscopic motion occurs generally in the form of rolls or hexagons (for variations see Koschmeider, 1977). In short, out of an initial state that is completely homogeneous there arises a well-ordered spatial pattern. Moreover, with further increases in the gradient the spatial pattern becomes oscillatory.

The Taylor instability, similarly a fluid phenomenon, is manifest in a situation in which water is enclosed between two cylinders that can be rotated in opposite directions. At rotation speeds below a critical value the fluid flow is laminar; above that value the flow becomes turbulent progressing toward stable, organized vortices.

The solid state laser provides a further example. Energy is pumped into a rod of material in which specific atoms are embedded and at the two end-faces of which are positioned mirrors. At small energy fluxes the laser operates as a lamp--the atoms emit lightwave tracks independently of each other. When the energy flux exceeds a critical value, all the atoms oscillate in phase emitting a single and very large wave track of light.

In these examples we see that with a change of scale macroscopic structure arises from a homogeneous state of affairs or from a state of affairs of lesser structure. A new stability that arises beyond a critical scale value may in turn give way to a further, different stability at higher scale values. In both the Bénard and Taylor situations, at supercritical values periodic pulsing characterizes the newer stabilities that replace those that appear at the critical value. One might conjecture that the origin of constraints--beginning as it must with low selectivity and imprecise function and gradually sharpening up to high specificity and narrow precise function (Pattee, 1973)--is interpretable, in part, as a succession of instabilities (Prigogine & Nicolis, 1971).

At all events, as a tentative response to the question posed above we can offer the proposal of Yates, Marsh and Iberall (1972) that at whatever scale we choose to observe nature, new constraints or regularities arise from an apparent continuum of "atomistic" particulars as a result of interactions among the particulars, constraints and a scale change in some parameter.

7. Essential and Nonessential Variables

Following Gel'fand and Tsetlin (1962, 1971), it can be assumed that the variables functionally linked by an equation of constraint or by a system of such equations can be partitioned into two classes: Essential variables which determine the function's topological qualities and nonessential variables which bring about marked changes in the value of the function but which leave the topological qualities of the function unaltered. Importantly, the classification of variables into essential and nonessential is not necessarily fixed--outside a range of magnitudes a nonessential variable may become essential and vice versa (see below). For Pattee, equations of constraint and the classification of variables into essential and nonessential are lumped together as "control". Our intuition is that it is more prudent to dissociate the two. We identify the classification of variables with control and the equations of constraint with coordination. To conserve the topological qualities of the relation enforced by a constraint requires that the essential variables be kept fixed and to introduce variation in these qualities without annihilating them requires that only the nonessential variables be changed. Here then is the rationalization for the coordination/control distinction: A constraint "coordinates" in the sense that it enforces (automatically) a relationship among several variables; the partitioning into essential and nonessential variables "controls" in the sense that it identifies the means by which the relationship can be systematically modified--qualitatively and quantitatively.

8. The Content of the Order Grain

To emphasize constraints and, therefore, to extend analysis to the relation grain is to farm out the causal responsibility that was exclusive to the order grain. What consequences does this have for the order grain of analysis? Recall the program conception of cellular state transitions; basically, check with DNA for <u>what</u> to do <u>when</u> the state of the cell is such-and-such. The program conception of DNA fixates the explanation of the epigenetic process at the order grain and requires, therefore, that the order grain be explicit on the type of state the cell is to assume and the point in a temporal sequence at which it is to assume that state. In raising the explanation to the relation grain (that is, the conception of DNA as constraint) the preceding evaluation of the order grain is rendered inaccurate; the predicates of the order grain <u>vis a vis</u> the epigenetic process can refer neither to systemic states nor to the order in which they are to occur.

In terms of the distinction just drawn between coordination and control, the relation grain is synonymous with coordination and the order grain is synonymous with control. By this synonymity, the predicates of the order grain are now semantically less fanciful referring only--at least under the present analysis--to the classification of variables; and control is logically less deep referring principally to changes in variables that selectively influence functional dependencies automatically enforced at the relation grain. These conceptual modifications, though roughly expressed, are consistent with the thrust of the coalitional style of inquiry which is to understand how systemic states and their order are not explicitly represented as <u>a priori</u> facts of the system but rather arise, from the mutualities among the grains, as necessary <u>a posteriori</u> facts (Kripke, 1971) of the system.

Non-equilibrium phenomena of the kind described above hint at one way in which systemic states may occur as necessary <u>a posteriori</u> facts without an <u>a priori</u>, explicit description. Put differently, they hint at how an organization or regularity can arise from within a system rather than being imposed upon it (cf. Fitch & Turvey, 1978). (To reiterate, on the machine conception of biological order, with its attachment to imperative languages and its fixation at the order grain of analysis, organization or regularity is more properly said to be owing to an agent or device that is outside the system exhibiting the said organization or regularity.) The point can be made in reference to a mammalian behavior. The stable states of quadruped locomotion at low velocities have in common an asymmetry of limbs of the same girdle--they are always half a period out of phase. At high velocities the stable states of quadruped locomotion are characterized by an in-phase relation of limbs of the same girdle (Grillner, 1975). The transition from an asymmetric gait to a symmetric gait tends to occur abruptly (Shik & Orlovskii, 1976). It need not be supposed that the differences among gaits are the effects of differences among programs of instructions which prescribe the kinematic details. The different gaits might well be interpreted as those quadruped stabilities, few in number (cf. Thom, 1975), that can arise pursuant to the instabilities wrought by scaling up muscle power.

The general point is that locomotory patterns are to be explained by an appeal to the concepts and tools that constitute non-equilibrium dynamics such as stability theory, bifurcation theory and fluctuation theory (Haken, 1977; Landauer, 1978; Prigogine, Nicolis, Herman and Lam, 1975; Thom, 1975) rather than by an appeal to formal programs of instructions. This general point is illustrated all the more forcefully by the facts of centipede locomotion. Thus, *Lithobius* (which normally moves its legs in waves with adjacent legs out of phase by one-seventh of a step) displays the asymmetric gaits of quadrupeds when all but two pairs of legs are amputated indifferent to the number of segments separating the pairs. Similarly, *Lithobius* displays the gaits of six-legged insects when all but three pairs of legs are amputated (von Holst, 1973).

9. Dissipative Structures and Cyclicity

An open system with nonlinearities that is maintained far from equilibrium is referred to as a "dissipative structure" (Prigogine and Nicolis, 1971). Simply, such structures conserve stability at the price of energy dissipation and, therefore, contrast with the classical entities of equilibrium thermodynamics which conserve energy and exhibit point or statical stability. What kind of stability do dissipative structures conserve? We ought to expect the form of the answer to be suggested by living systems so to them we turn for clues.

Consider two observations: Intracellular replication involves a (causal) cycle of events--DNA-->RNA-->Protein-->DNA; the behavior of bacteria in a life supporting medium is similarly cyclical--the bacteria grow and divide repetitively. Neither observation is especially exotic. Cyclicity appears to characterize many aspects of organismic behavior (Iberall, 1970; 1978). It was perhaps Goodwin (1963, 1970), who first took seriously the understanding that biological systems belong to a class of systems that are not stable in the classical point-stability sense but stable in relation to a closed cycle of events. On elaboration this understanding leads to a general principle, namely, that (the only) stability for a nonlinear system whose processes degrade large amounts of free energy is a *dynamic stability consisting of periodicities or cycles* (Minorski, 1962; Yates, Marsh & Iberall, 1972).

To what kind of periodicity or cycle is the stability of dissipative structures referred? Consider the familiar mass-spring system in which the moving mass is in contact with a non-ideal surface. It is a system that exchanges energy among potential, inertial and frictional processes as it displaces and it is a system that oscillates when certain relations hold among these dissipative processes. It is commonly represented by the linear, second-order equation:

$$M\ddot{x} + K\dot{x} + Sx = 0$$

where M is mass, K is the frictional coefficient, S is the stiffness coefficient and x is the displacement. More generally speaking, the equation is a representation of a decay or relaxation process; that is, it expresses the fact that the system does not persist in doing what it is doing (here, in this particular case, periodic displacing). For our mass-spring system to persist in doing what it is doing, and, therefore, for it to be more analogous to living forms, we would need to introduce a forcing function, F(t). The above equation, so modified, then reads:

$$M\ddot{x} + K\dot{x} + Sx = F(t)$$

In the modified equation we have a component that can oscillate (represented by the left hand side) and our desire is to provide a means for its continued oscillation. To this end a continuous forcing function is introduced. The problem now, however, is to identify a further mechanism, one that guarantees the persistence of the forcing function. Other than pursuing a strategy that mitigrates thermodynamic law, the provision of a source of persistence for F(t) is doomed to infinite regression. For it goes without saying that the forcing function does work and by thermodynamic law one cannot get something for nothing. The regress is avoided by letting energy be available in a constant, relatively "timeless" manner and by letting the work accomplished by the constant energy source be occasional (rather than continuous) and determined by the oscillatory component. This is tantamount to letting the left hand side of the above equation determine the form of the right hand side; that is, to the equating of persistent- or self-oscillation with a forced oscillation that is produced by a force which depends on the nature of the self-oscillation (cf. Andronow & Chaiken, 1949).

Consider the nature of clocks--periodic mechanisms with sustained oscillations. The three defining components of a clock are: (i) an oscillatory component, for simplicity, a pendulum; (ii) a (continuous, for our purposes) source of potential energy such as hanging weights or a wound spring; and (iii) a device--an escapement--that correlates (i) and (ii). In a pendulum clock the escapement is usually composed of two parts: an escape wheel with teeth that is lined by a wheel train to the energy source and an oscillatory component linked with the pendulum and carrying two projections, called pallets, that engage alternatively with the teeth of the escape wheel. At certain positions of the pendulum the wheel is allowed to escape (hence, "escapement") through a distance (or pitch) of one tooth. The release of the escapement wheel allows the hanging weights to descend a small distance or the coiled spring to uncoil slightly thus converting a small amount of potential energy into kinetic energy which is then "squirted," via the pallets, into the pendulum to keep it swinging. Generally, and ideally, the release of the escapement and the consequent "squirting" occur close to the pendulum's equilibrium point, that is where its kinetic energy is greatest. The important feature of the clock, therefore, is that the periodic tapping of energy to sustain the clock's oscillation (its ticking) depends solely on the position of the pendulum and not on time *per se*. In the foregoing sense Yates and Iberall (1973) offer the construal of a living system as an ensemble of "squirt" systems where the "squirtings" are made possible by degrading a good deal more free energy than is degraded in the drift toward equilibrium.

Our discussion has brought us to the following point: The stability of biological systems is in reference to cycles that are self-sustaining, non-conservative and non-linear. Cycles that meet these criteria are referred to as limit-cycles and among their important properties are numbered a tendency to a fixed amplitude and frequency no matter how disturbed, a tendency not to increase in amplitude when driven at their preferred frequency (that is, they are non-resonant) and a tendency to mutually entrain or synchronize (see Minorski, 1962; Oatley and Goodwin, 1971; Winfree, 1967).

In the foregoing remarks we have, in short, the motivation in many corners of contemporary theoretical biology for conceptualizing living systems, their component subsystems and their characteristic processes as ensembles of coupled and mutually entrained nonlinear oscillators, precisely, limit-cycles (Goodwin, 1970; Iberall, 1969; Nicolis & Prigogine, 1978; Walter, 1972; Yates, in press).

10. Coordinative Structures as Dissipative Structures

Let us now collect these arguments with reference to Bernstein's problem It can be argued--and it has been by Bernstein and those who have pursued his point of view--that the problem of degrees of freedom is resolved in large part by a systematic linking together of muscles in such a manner that the set of individual muscles is reduced to a much smaller set of muscle collectives (e.g. Gelfand et al., 1971; Turvey, 1977). A muscle linkage or a coordinative structure, as we have come to call it (Kelso, Southard & Goodman, 1979; Kugler & Turvey, in press; Turvey, Shaw & Mace, 1978), following from, but different from Easton's (1972, 1978) original usage, may be given a slightly more precise definition: It is a group of muscles often spanning a number of joints that is constrained to act as a single functional unit.

A coordinative structure is an organization defined over a relative continuum of "atomistic" particulars--individual muscles. Thus, the contractile states of the extensor muscles at ankle, knee and hip can very independently of each other but they are, in the act of locomotion, so organized as to preserve a constant proportionality across variations in their individual values (Grillner, 1975; Shik & Orlovskii, 1976). This organization does not express a state of equilibrium maintained without effort but rather it expresses a (marginally) stable steady-state maintained by a flux of energy, that is, by metabolic processes that degrade more free energy than the drift toward equilibrium. In short, a coordinative structure is a "squirt" system or dissipative structure; it is, in Iberall's (1977) terms, a thermodynamic engine that draws energy from a high potential source, rejects some to a lower potential energy sink and does work in a periodic, limit-cycle fashion.

Above we described the clock as epitomizing squirt systems. Here we pursue that example in order to buttress the equating of coordinative structure and dissipative structure. As noted, the specifications of a clock's oscillatory component and escapement (for example, length of pendulum, pitch of escapement wheel) determine when the oscillatory component will be squirted with energy and the duration of a squirt. (Recall that the timing of squirts relates to the design specifications in a principled way, precisely, they are phased so that the resulting forcing function exactly offsets the energy loss averaged over each cycle.) It is also the case that the specifications of the oscillatory component and escapement determine the amount of an energy squirt. Owing to the linkage between the escapement wheel and the potential energy source, the degree of rotation of the escapement wheel per escape determines the distance through which the hanging weights descend or the amount by which the coiled spring uncoils. That is, the design specifications determine how much of the available potential energy is converted, pursuant to an escape, to kinetic energy.

Of course, as the hanging weights approach ground level or as the spring becomes more unwound the magnitude of the available potential energy will decrease and, in consequence, so should the magnitude of the sustaining pulses of kinetic energy. In the manufacturing of clocks precautions are taken (via contrivances) to insure that the tapping of potential energy yields constant injections of kinetic energy. For our purposes, however, we wish to consider the case where such precautionary measures are absent. That is to say, we wish to consider the kind of clock in which the absolute amount of kinetic energy injected into the oscillatory component varies with the absolute amount of potential energy that is made available for work. Our motive for introducing this caveat is to facilitate the parallelism between clocks and coordinative structures. The latter, necessarily, feed on a power source that is variable. Thus, the step cycles of locomotion partake of the energy released by the noradrenergic system; as this power source is scaled upwards the speed of locomotion increases.

Now in a clock where the magnitude of injected kinetic energy is sensitive to scale changes in the power supply we can expect the velocity and amplitude of the oscillatory component's motions to be likewise sensitive and to reflect these scale changes.

The design specifications, however, guarantee that certain features of the clock's behavior will hold invariant over increases and decreases in power. Thus, the timing and duration of squirts will be independent of their magnitude and will remain roughly the same relative to the time frame--here, a period of oscillation. Moreover, the magnitude of a squirt will be some fixed proportion of the magnitude of the power supply--the potential energy stored in the weights or spring.

The constraint on the dynamics of individual muscles and joints composing a coordinative structure can be likened to the design specifications of the clock's oscillatory component and escapement. And the chemical energy liberated to be used for maintaining the constraint can be likened to the clock's source of potential energy. On this metaphor, a coordinative structure is an autonomous system in the conventional mathematical sense that the forcing function is not explicitly dependent on time. The "timing" of impulses does not require a separate device but arises necessarily from the design specifications--the equations of constraint--of the muscle collective. The significance of the latter to Bernstein's problem is obvious.

The equation of coordinative structures and self-sustaining, thermodynamically real oscillators (such as clocks) has been established to this point solely on rational grounds. As we shall see, however, the equation is befitting the empirical results and provides a principled reason for them. The essence of the scale independencies just noted for the clock is that the form of the forcing function is logically independent of the power supply; and <u>it is this very distinction which appears to mark the behavior of a group of muscles constrained to act as a functional unit</u>.

In freely locomoting cats, increases in velocity result from increases in the absolute magnitude of muscle activity during the E3 phase (see Grillner, 1975) but these increases are not accompanied by changes in the timing of muscle activity relative to the step cycle (Engberg & Lundberg, 1969). Moreover, the scaling upwards of the electromyographic activity seems to grade evenly over the extensors so that fixed ratios of activity are maintained. With regard to postural maintenance, Nashner (1977) has observed that over wide variations in upright posture brought about by rotation of the ankles, the ratios and sequencing of electromyographic activity in the muscles of the ankle, knee and hip remain fixed. For movements of the forearm inertial variation seems not to affect the timing of activity in the agonist-antagonist synergy while pronouncedly influencing the overall magnitude of activity (Lestienne, 1979). Similarly, increases in stress and rate of speaking bring about changes in magnitude of electromyographic activity without altering the temporal relationship between onset of tongue body muscles (genioglossus) and offset of lip gesture (orbicularis oris group) (Harris, personal communication).

Taking a kinematic rather than electromyographic perspective there is the well-established feature of cursive handwriting that the timing of strokes remains fixed over changes in letter size and unexpected increases in friction between pen and paper (cf. Hollerbach, 1978; Denier van der Gon & Thuring, 1965). In like vein, following full-mouth tooth extraction and complete removal of the alveolar ridge speakers maintain transition time constant for lingual palatal contact for /t/ in the word /thats/ in spite of displacement and velocity changes in jaw and tongue tip (Zimmerman, Kelso & Lander, in press). Similarly, the timing relations of the upper limbs during the performance of a task involving different spatial demands remains invariant over changes in the magnitude of force produced by each limb (Kelso, et al., 1979a,b). Finally it is commonplace for the frequency of a movement to remain fixed over scale changes in the forces applied. Thus, insect flight is generally regulated through changes in the amplitude of wing beat with frequency of wing beat held invariant (see Srinivasan, 1977). Similarly, if a fish has to drag a load during swimming it will increase movement amplitude and thereby the force produced while maintaining the same frequency of undulatory motion (Webb, 1971).

In sum, a dissociation of power and timing and a fixed proportioning of activity characterize a set of relatively independent muscles that appear to be bound together, temporarily, as a unit. By the arguments given here these properties of a muscle collective are by no means exotic and arbitrary. They are, to the contrary, the necessary concommitants of a (universal?) thermodynamic design principle for autonomous systems. The ingredients of autonomy, as we have seen, are a time independent source of potential energy and a time-independent means that transforms that energy and does work in a periodic fashion. Given these ingredients, we might suppose, in the spirit of Thompson (1917/1942), Rashevsky (1950) and Thom

(1975) (see Kugler, Kelso & Turvey, in press), that there are relatively few stable recipes. Thus self-sustaining devices can distinguish in many ways materially (consider, for example, the material distinctions between a grandfather clock and a coordinative structure) but they can distinguish in very few ways functionally, if at all. The clock example, therefore, should be viewed as exemplifying a <u>function</u> (common to both clocks and coordinative structures) rather than as exemplifying a <u>mechanism</u>.

From the perspective of Bernstein's problem, designing locomotion in terms of coupled limit cycle oscillators presents a distinct advantage. The property to be underlined here is that of the mutual synchronization of interacting limit cycle oscillators; mutual synchronization--entrainment--is not possible for oscillators of the more familiar kind, namely, linear harmonic oscillators. A fairly convincing argument can be made that in locomotion the individual limbs function as distinct coordinative structures (Shik & Orlovskii, 1976) which, by the identity above, means distinct limit cycle oscillators. If a quadruped is locomoting in a given gait and one of its limbs--for whatever reason--is momentarily perturbed then (as long as the perturbation is not too extreme, so as to precipitate falling) the mutual entrainment of the limbs <u>qua</u> limit cycle oscillators would restore the phase relations that preceded the perturbation. More generally, mutual entrainment would guarantee the preservation of a gait over that range of velocities (or muscle power) for which it is a stable quadruped state. Of course, we can easily imagine the preservation of gait to be owing to processes that iteratively refer to a set point or a collection of set points. The elegant analysis of Shik and Orlovskii (1965) is interpretable in such control theory terms (Fowler & Turvey, 1976). However, we have given reasons for preferring explanatory principles which allow organization and regulation as necessary <u>a posteriori</u> facts and which avoid attributing <u>sui generis</u> status to variables at the value grain. Set points or reference signals, as noted, necessarily assume <u>sui generis</u> status in control theory. There are a goodly number of other rhythmic behavioral phenomena that appear to call out for interpretation in terms of coupled limit cycle oscillators. Many have been reported by von Holst (1973) and their significance has not gone unnoticed (e.g. Stein, 1977).

Let us proceed therefore to explore the thesis that where a group of muscles functions as a single, coherent unit it is a limit cycle oscillator. And that limit cycle oscillation, characteristic as it is of dissipative structures, identifies the model construct that we seek.

Limit cycle oscillation, by definition, arises in the context of nonlinearities and it will prove beneficial to our understanding of control and coordination to dwell on the important distinction between linearity and nonlinearity in systemic behavior. This distinction is a natural extension of that drawn above between nonessential and essential variables. We will in what follows identify linear with nonessential and nonlinear with essential. These identities are somewhat eccentric but they permit us to make the points we wish to make as well as indexing our current (journeyman) understanding of the issues involved in the contrasting of linear and nonlinear systems.

11. <u>Linearity and nonlinearity</u>

Let us begin with the notion of stability. Dynamical systems are modelled as "systems" of differential equations. The solution to a differential equation is, of course, not a number or set of numbers but a family of functions. To study differential equations one proceeds along two routes, the quantitative and the qualitative, with the latter the only course of study for those equations--usually the most interesting--that resist quantitative analysis. In pursuing the qualitative or geometric route (first promoted by Poincaré) what becomes important is the phase portrait, a study of the geometrical or structural characterization of the trajectories representing the range of solution graphs. The phase portrait permits the identification of qualitative properties of dynamical systems as modeled by differential equations, for example, periodicities, equilibria (as singular points), types of stable regions etc. One definition of structural stability (cf. Andronov & Chaikin, 1949; Thom, 1970) follows: A differential equation or a system of differential equations that is structurally stable preserves the qualitative or topological characteristics of its entire phase portrait in the face of variations in its parameters. [See, however, Berlinski (1977) for an informed evaluation of the stability concept.]

In the light of the foregoing, consider the linear harmonic oscillator modeled by the equation given above, namely:

$$M\ddot{x} + K\dot{x} + Sx = 0$$

This system is structurally neutral in that a change in a dissipative parameter may bring about marked changes in the topology of the system's dynamical character. For example, in the absence of friction, solutions are periodic; with friction solutions approach zero or infinity depending on the parameter value. By contrast, in a system with nonlinearities such as expressed by the celebrated van der Pol equation:

$$\ddot{x} - K(1 - x^2)\,\dot{x} + x - 0$$

for all positive values of the dissipative parameter K there is a topologically invariant limit cycle solution. A nonlinear system tends to be structurally stable.

Speaking informally, a linear system is structurally neutral in the sense that it has no preferred solution or set of solutions. The situation resembles that of a billiard ball on a smooth billard table--the ball will remain at rest wherever it is placed. The phase space through which the trajectories of a linear system are moved by varying the parameters is a space that is flat and smooth like the billiard table--any location is as good as any other. That is to say, the phase space can be populated evenly with trajectories; there are no locations, no attractor points, where the trajectories become especially and consistently dense.

By way of contrast, and again speaking informally, a nonlinear system is structurally stable in the sense that it has a preferred solution or set of solutions. The trajectories of a nonlinear system move in a phase space which is not flat and smooth but wrinkled and indented with attractor points or sets, like limit cycles, on which the trajectories consistently converge.

There is, importantly, a positive reading to be given to the structural instability of a linear system: A different behavior follows from a different setting of the system's parameters. The simple mass-spring system is a topical illustration of this characteristic; the length at which the spring equilibrates following a displacement is not fixed but varies systematically with variations in mass, stiffness and friction. One might say that a linear system exhibits a certain kind of precision and a certain kind of flexibility in the sense that its behavior reflects its parameterization. We wish to make something of this point--that a linear system buys into precision and flexibility at the cost of structural stability in contrast to a nonlinear system which buys into structural stability at the cost of precision and flexibility.

The preceding has emphasized how a change in some aspect of a linear differential equation or a set of such equations affects the global topology of its solution space. Let us now focus on the nature of the individual trajectories in the solution space. It is standard procedure to treat systems of linear differential equations in terms of linear transformations between two vector spaces and it is in this context, of abstract vector spaces, that linearity as a concept is best appreciated. In the mapping from one vector space to another, from "input" to "output," a linear system possesses two defining properties: Superposition and proportionality. By superposition is meant that if several inputs are simultaneously applied to the system, their total effect is the same as that resulting from the superposition of individual effects acting on each input separately; in linear theory terms, $L(X_1+ X_2 . . . + X_n) = L(X_1) + L(X_2) + . . . + L(X_n)$. And by proportionality is meant that if all the inputs to a system are multiplied by the same factor, then the responses are multiplied by the same factor; in linear theory terms, $L(\alpha X_1, \alpha X_2 . . . \alpha X_n) = \alpha L(X_1, X_2 . . . X_n)$. In brief, for a linear system there is always a tight or "precise" coupling of input to output. The degrees of freedom captured in the input are preserved in the output. This fundamental feature of a linear system is consonant with the phase space-as-billiard table analogy--to paraphrase, for a linear system there are no preferred outputs.

Neither proportionality nor superposition are properties of a nonlinear system and this is consonant with the inhomegeneity of the phase space of a nonlinear system. Because there are attractor points or sets identifying preferred outputs, the mapping from input to output by a nonlinear system is many-to-one (more generally, many-to-few) in comparison to the one-to-one mapping of linear systems. A nonlinear system is "imprecise" in that it does not preserve at output the degrees of freedom at input.

To summarize, we have understood two major distinctions between linear and nonlinear systems, namely, that they distinguish in their sensitivity to parameter changes and in their coupling of inputs to outputs. It remains for us to make one final but important point. The behavior of a nonlinear system may be dramatically altered by the introduction of certain inputs (defined in terms of amplitude or type of frequency) at certain times (defined in terms of phase relationships). Thus at critical times an input with criterial properties may bring about a jump from one preferred output or stability to another. Occasionally, therefore, a nonlinear system will appear to be closely coupled to its input when in fact there is marked independence.

12. Essential and nonessential variables revisted

It is unquestionable that the dynamical systems of interest to biology involve nonlinearities; complexity begets nonlinearity, as Berlinski (1977) remarks and nonlinearity begets autonomy, as Prigogine (Prigogine & Nicolis, 1971; Prigogine, 1976) and Haken (1977) underscore. The fact of nonlinearity in the control and coordination of movement is duly recognized by the equating of coordinative structures with dissipative structures. However, if systems of muscles are necessarily nonlinear then are we not faced by a paradox? In the senses detailed above, a nonlinear system is stable but not precise whereas the activity of an animal in reference to its surroundings seems to demand a measure of <u>both</u> stability and precision.

If the periodicities of locomotion, the wavelike excursions in the successive joint changes within a limb and between limbs (see Arshavskii et al., 1965), were affected by slight variations in dissipative parameters than the integrity of locomotion as an act would be easily infirmed. As it is, the locomotory pattern is largely immune to wide variations in frictional forces, supplied by surface and by medium, and in the mass that is transported. In the extreme, cats swim as they walk (Miller, van der Burg & van der Meche, 1975), amphibious newts undulate identically in water and on land and donkeys (it seems) walk the same with and without heavy burdens. At the same time, however, it is patently obvious that these locomotory activities like other activities can be finely tailored to the exigencies of the environment (see Lee, this volume; Turvey & Remez, 1978). The question, therefore, is how do nonlinear systems that are basically imprecise though stable condense out--in a fashion suggestive of linear systems--kinematic details that are precisely related to environmental states of affairs? This question may be novel in the form that it takes but it is not novel in the fundamental concern that it expresses (viz., the tuning issue; Greene, 1972, 1975; Gurfinkel et al., 1971; Turvey, 1977).

Let us take another look at the linear/nonlinear distinction. Rather than viewing it as a distinction between systems let us view it as a distinction <u>within</u> a system, more precisely, a distinction between the behaviors of a system that would, by mathematical convention, be termed a nonlinear system. Imagine a differential equation in which <u>some</u> of the terms are products of variables or powers of variables and/or where one or more of the coefficients depend on the function or derivatives of the function being determined. Conventionally this is a nonlinear equation but the point to be emphasized is that there are distinctively different contributions to the dynamics of the system that the equation represents, some of which are nonlinear and some of which are linear. Put differently, all real systems contain nonlinearities but they also contain linearities which is to say that all real systems are both structurally stable and structurally neutral. How is the latter to be understood? To the global perspective on the concept of structural stability that was given above we will need to add a more local perspective. Imagine a (nonlinear) function of several arguments. The topology of the space that the function generates for variations in its arguments will be populated (unevenly) by points of inflection. A given <u>path</u> through the space can be termed structurally stable if the path contains an inflection point defining a preferred location and structurally neutral if the path contains no inflection points, that is, no points of preference. A family of structurally stable paths that inflect at a common value identifies a structurally stable region; and, by the same token, a family of structurally neutral paths identifies a structurally neutral region. Obviously, for a region of the latter kind linear theory is the appropriate mathematical tool.

It should be emphasized that an inflection point identifies a stable configuration of the system's dimensions, that is, a point about which the dimensions will tend to configure subsequent to perturbation. Even in a potential system, in which energy is a dimension (a system of the kind to be examined in detail below), a point of inflection is not strictly energy referential, say, a point of minimal energy dissipation; it is, more precisely, system or function referential in that it is a signature of the system or function as a whole.

The foregoing remarks can be illustrated more clearly by considering the function $z = f(x,y)$ plotted in Figure 1. (The precise nature of the variables is immaterial to the illustration.) The gradient dynamics of

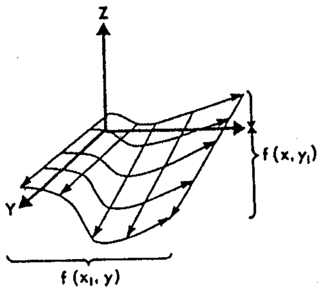

Figure 1

the manifold associated with the function $f(x,y)$ can be intuitively described as follows. There is a valley bordered by two chains of mountains with geometric gradients which are not symmetrical. Starting with a point of origin (x,y_i) on the y-axis a traveler moving in the direction of increasing x will move down a ramplike gradient, through a small valley, and up an ascending slope. The traveler's path describes a phase portrait associated with the function $f(x,y_i)$. Starting from a new y_i the traveler again moves off the y-axis in the direction of increasing x and discovers a new geometric path moving down a gentle slope, through a valley, and up an ascending slope. Figure 2 describes a family of such paths where each is associated with a different y_i. The important feature in this family of curves is the invariant topological profile associated with each curve. The topological invariance is geometrically portrayed in the inflection point or valley revealed in each path. Thus the family of curves is

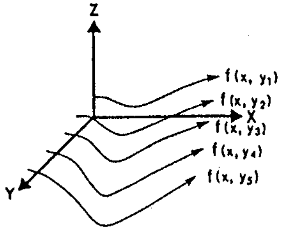

Figure 2

describable by a qualitatively invariant set of nonlinear differential equations and they identify a local region in which the function is "structurally stable".

Let us now consider the same function $f(x,y)$ from the perspective of the y-variable, $f(x_i, y)$. Starting from a point (x_i,y) on the x-axis, a traveler moving in the direction of increasing y journeys along a relatively flat geometric trajectory. Figure 3 describes a family of such curves generated from various starting points on the x-axis, $f(x_i,y)$. The family of curves generated from this orientation has a geometric profile that is topologically homogeneous. There are no inflection points in these curves, no topological inhomogeneities. The paths form a family

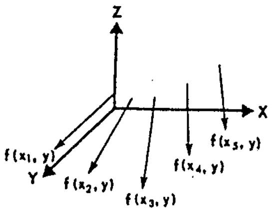

Figure 3

of curves describable by a set of linear differential equations. Furthermore, since there are no inflection points in the topological space, the function is "structurally neutral" within the locally described region. It is important to note that a family of linear equations need not describe a geometrically flat space. A family of linear equations could describe a curving ascending or descending gradient with the only restriction being a prohibition of inflection points on the surface.

The partitioning of the function into components associated with linear and nonlinear behavior is not necessarily "fixed". That is to say in one region a variable may have a linear relationship to the function but in another region its relationship to the function is nonlinear. Figure 4 describes a family of curves in which the behavior of the function undergoes a transformation from linear to nonlinear. The curves described by

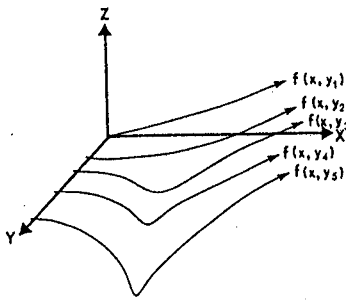

Figure 4

$f(x,y_1)$ and $f(x,y_2)$ behave linearly while the curves described by $f(x,y_3)$, $f(x,y_4)$, $f(x,y_5)$ behave nonlinearly. At the same time, however, the transformation need not be reflected in the other functional variables. Figure 5 describes a function in which there is a functional transformation in the $f(x,y_i)$ relationship and yet no transformation in the $f(x_i,y)$ relationship. Recently, Thom (1975) has provided a systematic study of these transition regions in his theory of "catastrophes". Catastrophes, for Thom, are the dramatic and sudden "jumps" in behavior associated with various topological transformations. These transformations occur when systemic variables are "scaled-up" beyond certain limits. At these points sudden qualitative changes occur in the system's behavior. This provides part of the rationale for terming such regions "structurally unstable." These regions are both exploited and avoided in the organization of natural functions. For example, in the case of an action potential in a biological system, when the voltage gradient is driven beyond -70 mvolts in the direction of zero a qualitative change occurs in the membrane's

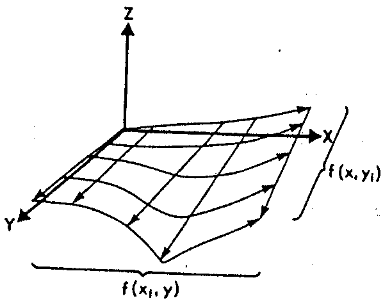

Figure 5

permeability allowing for an influx of sodium and thus depolarization. The behavioral catastrophe is associated with a qualitative change in the topological complexity of the underlying function. In this example the structurally unstable region is exploited by the biological system.

Let us now draw the identity between linear behavior and nonessential variables and nonlinear behavior and essential variables. As noted earlier essential variables determine the function's topological qualities, whereas nonessential variables determine the possible scalar transformations over the topological complexity. Following Gel'fand and Tsetlin (1962, 1971), we will consider a function "well-organized" when the function can be partitioned into these two classes of variables: essential and nonessential. For example, Figures 6 and 7 are not "well-

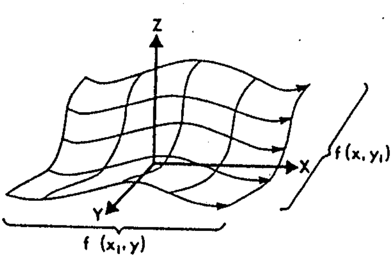

Figure 6

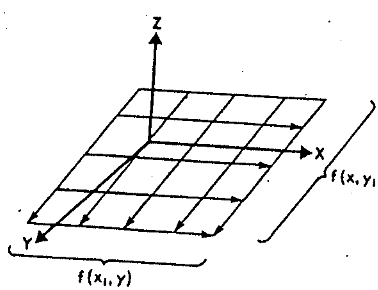

Figure 7

organized". Figure 6 defines a function composed of two essential variables, while Figure 7 defines a function composed of two nonessential variables. Given the above identity, we can now say that linear variables are associated with nonessential variables and therefore with control and nonlinear variables are associated with essential variables and therefore with coordination. Furthermore functions that are "well-organized" may be said to be optimally organized with respect to components of control and coordination. We proceed to consider this claim in more detail.

By coordination we refer to the function's regions of "structural stability" as specified by the topological properties of qualitative complexity. For example, a function will <u>maximally conserve stability</u> when organized at regions on the topological manifold specifying inflection points. Deviations from these regions will be associated with a decrease in functional stability and an increase in energy dissipation. Therefore, for maximum conservation of stability and minimal dissipation of energy a system is optimally organized around topological points of inflection. As noted above, <u>essential variables are associated with a system's coordination by virtue of the fact that they determine the inflection points which specify points of maximum conservation of systemic stability</u>.

By control we refer to the function's regions of "neutral stability" as specified by the scalar properties associated with the nonessential variables. For example, stability will be minimally disrupted and energy dissipation minimally incurred at points on the topological manifold that preserve invariant the essential variables at inflection points. The advantage gained by the nonessential variable is flexibility. A system organized with only nonlinear variables results in either saddlepoints or singularities around the inflection points. The result of this style of organization is too much stability or marginal instability for the system. In the case of the singularity, geometrically portrayed as a point on the bottom of a conic projection, the function is so stable that deviations in any direction will be resisted with a tendency to return to the singularity. In the case of a saddlepoint, geometrically portrayed as two orthogonally coupled horseshoes with one facing up and the other facing down (the reader is reminded that the name "saddlepoint" comes from its resemblance to a saddle), the function is unstable with any deviation away from the intersection point in the direction of the variable pointing down, while the function is stable for any deviation in the direction of the variable facing upwards. In short, this style of organization has little flexibility and only marginal stability. However, if a nonessential variable is introduced to complement the stability of an essential variable, then flexibility is added to the functional organization. Since the nonessential variable defines a structurally neutral region in the manifold, an organization can be realized in which the essential variable is "fixed" at the inflection point while the nonessential variable moves through a path which does not disturb the function's stability and minimally incurs dissipation of energy.

Returning to Figure 1 we see that such an organization exists when the function maintains the essential variable in the valley and movement up the valley is specified by variations in the nonessential variable. This style of organization involves the exploitation of stability specified by the essential variable (that is, for maximum coordination maintain the function in the valley), while introducing maximum flexibility for precision through deviation along the nonessential variable (that is, for maximum control move the function through the valley).

13. The Behavior of a Force-driven Harmonic Oscillator

Let us now consider a natural dynamic function--that of a force-driven harmonic oscillator--in terms of the above arguments for a linear/non-linear style of organization. The dynamic behavior of the oscillatory system is described by the following relation:

$$F = \frac{\theta L M}{\left[\frac{1}{(\omega_0^2 - \omega^2)^2 + 4\left(\frac{B}{2M}\right)\omega^2}\right]^{1/2}}$$

Driving force (F) = newtons
Amplitude (θ) = degrees
Length (L) = meters
Mass (M) = kilograms

Resonant frequency (ω_0) = hertz
Actual frequency (ω) = hertz
Damping coefficient (B) = kilograms/seconds
Gravity (G) = Meters/second^2

$$\text{where:} \quad \omega_o = \frac{1}{2\pi\sqrt{L/G}}$$

General examples of partial geometric manifolds associated with the above functional organization are presented in Figures 8 and 9. The plotted

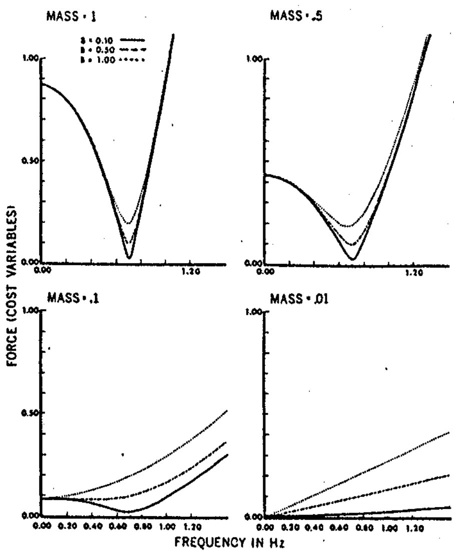

Figure 8

curves describe the system's behavior from the perspective of manipulation on the frequency variable. For Figure 8, each curve represents different parameter settings of the mass and damping coefficient variables. For Figure 9, each curve represents different parameter settings of mass and length variables. The parameters of amplitude, length and gravity are held constant over each set of graphs. Since these graphs are plotted in a two-dimensional space, a third dimensional variable is manipulated between each of the three curves in each graph and a fourth dimensional variable is manipulated between each of the four graphs in each series.

Let us begin by examining the geometric properties associated with the curves in Figure 8. When viewed from a three-dimensional perspective, the upper left graph of Figure 8 reveals a valley extending out towards the viewer with asymmetrically ascending gradients to the left and right of the valley. The x-axis represents frequency, the y-axis represents force (or cost variables) and what would be the third-dimensional z-axis (represented by the three separately plotted curves) indexes a damping coefficient (B). A closer examination of the geometric properties reveals that the valley extending out to the viewer possesses a slightly ascending slope in the direction of increasing damping coefficient. Briefly, the three curves describe a family qualitatively similar to those portrayed in Figure 2. Both families of curves depict nonlinear systems and both functions are structurally stable in their respective local regions.

Moving from the upper left to the upper right graph in Figure 8, the function has the parameter of mass changed from 1.0 kilograms to 0.5 kilograms. We notice that as the system's mass is reduced the slope of the ascending gradients surrounding the valley is also reduced. Further variations in the slope's geometric properties are associated with changes in damping coefficient. As the damping coefficient increases, the slopes of the corresponding geometric gradients decrease. The important property to note is that as the function changes its organization with new parameter settings of mass and damping coefficient, there is a corresponding change in the underlying geometric properties. In particular, <u>decreases</u> in slope are associated, on the one hand, with <u>decreases</u> in mass and, on the other hand, with <u>increases</u> in damping coefficient. Let us consider briefly the nature of the "slope". Not only is slope sensitive to changes in mass and damping coefficient, but it is also sensitive to a wide variety of combinations of the other variables that define the system's dimensions such as amplitude, gravity and length. Since slope is a "dimensionless" value, manipulation by the various dimensional variables imposes only "scale" changes on the value of the slope. In essence <u>slope specifies a critical ratio of the system's defining dimensions where the ratio is a dimensionless number whose value is "system-scaled" in association with changing system variables</u>. We term such a ratio a "system-scaled variable."

A second "system-scaled" variable is the geometric variable of inflection. In Figure 8 the upper left and right graphs reveal a valley extending out towards the viewer. The valley is formed by a series of inflection points generated over a family of parameterizations on the damping coefficient. We noted earlier that a function exhibiting stability of inflection points within a local region is termed "structurally stable." With respect to the system's behavior, maximum stability and minimum energy dissipation is incurred when the system is organized with parameters specifying the region of the valley. For an oscillating system the region specified by the valley is termed the region of "resonance." The variable of inflection shares similar characteristics with the variable of slope. Both slope and inflection have "dimensionless values" and both are "system-scaled variables." This becomes more apparent in the case of the inflection when we examine the lower left graph of Figure 8. Moving from the upper right to the lower left graph the system's mass parameter has been scaled down from 0.5 kilograms to 0.1 kilograms. Due to the scale change the upper two curves of the lower left graph exhibit no inflections, whereas the bottom curve still reveals an inflection property. This set of curves is similar to those described in Figure 5. In both cases the function describing the local regions are termed "structurally unstable." The structurally instability is due to the annihilation of inflection properties. Scaling down further on the mass parameter, the lower right graph reveals a set of curves in which no inflection properties are present. Under this scale transformation all the inflection points are annihilated. This set of curves is similar to those described in Figure 3. The function for both cases is termed "structurally neutral" since the local phase portrait in both cases is topologically homogeneous within the entire local regions. Thus, as before with slope, the geometric property of inflection is sensitive to scale changes in the parameter of mass. In fact further scale changes in the inflection property are associated with changes in damping coefficient, gravity and length. In short, the inflection point specifies a critical ratio of the system's defining dimensions where the ratio is a dimensionless number whose value is "system-scaled" in association with changing system variables.

Figure 9 is a set of graphs similar to those in Figure 8 except that instead of the damping coefficient changing within each graph, length is

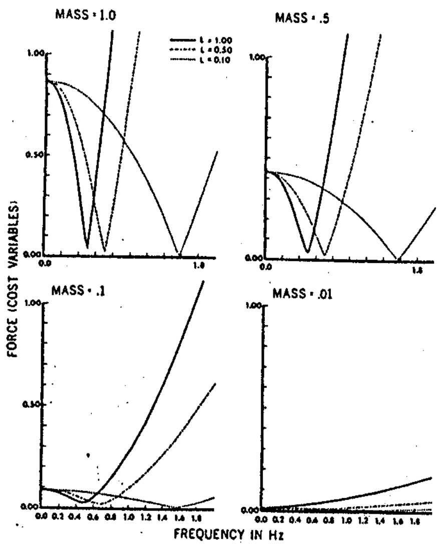

Figure 9

varied. The upper left graph describes a set of curves, each associated with a different length oscillator. We note that each curve exhibits an inflection point at a different frequency value. As we scale down on mass from 1.0 kilograms to 0.5 kilograms, we see in the upper right graph that scale changes have occurred in the slope variable but not in the inflection variable. Scaling mass down further to 0.1 kilograms reveals in the lower left graph further changes in the slope variable with no change as yet in the inflection variable. However, when the mass is scaled down to 0.01 kilograms in the lower right graph we now note that the inflection variable has changed. In all three curves the inflection property has been annihilated. We also note further changes in the slope variable. Under this final transformation the system's resonance property is annihilated.

Let us conclude this section with a brief summary. Slope and inflection are dimensionless geometric properties that are continuously scaled to changing dimensions of the system. The nature of the change in the slope variable is continuous while the nature of the change in the inflection variable is discrete. We will argue in the following section that the status of a variable in terms of essential and nonessential functional components is distinguished on the basis of geometric information in a vocabulary of dimensionless system-scaled variables. We have described two such variables exhibited by the properties of slope and inflection.

14. Information as Form

Again, to bring our arguments into focus, we return to Bernstein's problem. Ideally, the model construct that is sought should be (1) an autonomous system in that the energy flux by which the system is sustained is determined by properties intrinsic to the system; and (2) a self-organizing system in that the information flux by which the system is controlled and coordinated is, at one and the same time, determined by the system's dynamics and modulatory of them. We have given a conceptualization of coordinative structure that is consonant with (1); our task now is to pursue a conceptualization consonant with (2). In paraphrase, and in the terminology of Pattee (1972, 1977), (2) above is the requirement that the sought-after model construct refer to a system that writes and reads information about itself, that is to say, that it be a self-describing, self-writing, and self-reading system. (The terms "writing" and "reading" convey the flavor of the requirement--but they should not be taken too literally.)

What is at issue, first and foremost, is the nature of the self-description. What are the predicates in terms of which a self-organizing system describes itself? Suppose that the predicates are quantitative, precisely, values on the dimensions over which the system's dynamics are defined. It would follow, therefore, that at any given point in time the self-description would be a set of values, a vector. But a vector space as an information space is homogeneous: No vector can of itself mean any more or less to the system than any other vector. Any biasing of the vector space, any ascription of meaning, would have to originate externally, that is, the semantics would have to be "added" to the information space by a logically separable event such as a function which maps the vectors to a memory or matches them with a reference. A very similar conception of information to that just given is the popular simile of information as a finite sequence of symbols (like letters) taken from an alphabet and organized by a linear syntax. This linguistic conception suffers the same infirmity as the quantitative conception, namely, that it is a purely formal description requiring a separate step of semantic adumbration.

It would appear that the requirements of self-organization are ill-served by quantitative and linguistic interpretations of information (see Kugler et al., in press, for a more detailed discussion). A more suitable interpretation should be sought, one in which the formal description of a systemic state is not numerically distinct from the semantic description thereby avoiding a regress to an external, interpretative device.

Consider again a major theme of the foregoing section--that a "well-organized" function, a function that is both stable and flexible, is one in which the variables separate into nonlinear or essential and linear or nonessential. Assuming that the self-organizing system of present concerns is also a well-organized system then we can recognize that the interpretation of information that we seek should readily distinguish between essential and nonessential variables. Recall that the separation of variables is not fixed, not given a priori, but rather it is a distinction that is given a posteriori in the local aspects of the system's dynamics. In the analyses of the preceding two sections we saw how the two classes of variables may distinguish topologically. Membership in the classes is defined by topologies that are invariant over variations in dimensional values. On those analyses, therefore, we forward the tentative suggestion that the conception of information that we want is qualitative rather than quantitative; that information is, first and foremost, morphological--a form--and that the morphology of a system's dynamics is information about the system in the sense of specificity to the system. A separate, extra-dynamical step is therefore obviated. Information conceived morphologically may require detection but it does not require interpretation.

It is of no little significance that the specificity criterion for this conception of information is mandated by the ecological approach to perception, guided as it is by a commitment to realism (see Gibson, 1966, 1979; Mace, 1977; Shaw, et al., in press; Turvey & Shaw, 1979). It should also be recognized that it is a morphological approach to information that is being promoted by Thom (1972, 1975) and, moreover, that the need to focus on the geometry of dynamics has its precedent in the efforts of physicists to remove gravity from the list of global explanatory principles, sui generis (see Wheeler, 1962).

Let us highlight one of the many consequences of conceptualizing information morphologically. In Figure 1 an inflection point in the x variable is preserved over a range of variation in the y variable; in Figure 7 an inflection point in the frequency variable is preserved over a range of variation in the variables of mass and damping. In both cases there is a qualitative invariant even though the quantities, the coordinates, that mark the locations in the phase space are variable. Slope changes in a continuous quantitative fashion while inflection changes in a discrete quantitative fashion. As noted earlier, both slope and inflection are dimensionless system-scaled variables (see Bridgeman, 1922, for a simple and elegant account, and Lee this volume). The point to be appreciated is that morphological information is dimensionless and always system-scaled.

Now if we are to take the morphological approach seriously then we have to suppose that the proper perspective on the traditional channels of "information" for motor systems, the afferent paths, cannot be that they yield quantitative dimensional values to be referred to some preestablished dimensional quantity for their meaning and regulation. Rather, they must be viewed as contributing, together with the traditionally defined efferent paths and the muscles, to the form of a muscle system's dimensionless dynamics. In short, the efferents and afferents both contribute system-scaling variables. Put differently, the morphological perspective on information renders it unlikely that the contribution of traditionally defined afference is dimension specific. Moreover, it suggests that a collective of muscles will not be debilitated by the elimination of any given afferent source or even by the elimination of all afferent sources; although the stability and flexibility of the collective may be less than ideal. This is to say, that in the absence of the full complement of contributions to the information space, the topological characteristics specifying essential and nonessential dimensions will remain, but their system-scaling and articulation within the space may be less emphatic and, therefore, less "detectable."

This latter remark leads into one final contrast that would, under a more complete explication, be assiduously drawn. The distinction between nonlinear and linear is a formal mathematical distinction; that between essential and nonessential is a pragmatic distinction. Within a given range of variation a dimension may continue to meet the formal criteria for nonlinearity but it may not continue to meet the pragmatic criteria for essential. The essential/nonessential contrast owes an obligation to physical realities which the nonlinear/linear contrast does not. We are saying, in short, that the essential/nonessential distinction for a system is system referential and abides by the resolving power, the self-sensitivity, of the system.

15. A Geometrodynamic Perspective on Muscular Forces.

To reiterate, the hallmark of autonomy is that the energy flux, or forcing function, does not depend explicitly on time but rather on properties intrinsic to the system's design. The clock has been given as exemplary of self-sustaining thermodynamic engines: The form of the energy injections that maintain the clock's activity are determined by the design specifications of the escapement and oscillatory component. And, as noted, the design specifications of the clock are like a constraint which functionally and systematically binds a group of muscles--the behavioral effects in the two cases are qualitatively similar.

Focusing on the activity of a constrained collection of muscles, it behooves us to recognize two fluxes of force. There are, on the one hand the muscular forces and on the other hand the reactive, frictional, gravitational and contact forces into which the flux of muscular forces is inserted. The larger point of Bernstein's (1967) approach to movement was the necessity of considering the totality of forces, a point that others have duly expressed (e.g., Fowler and Turvey, 1978). Because the nonmuscular forces are in flux, the muscular forces cannot be prescribed temporally or quantitatively. To successfully effect a movement the animal must generate a flux of muscular forces that together with the flux of non-muscular forces suffices to achieve its aim.

How is a requisite flux of muscular forces generated? Or, putting the question into a specific form, one that is relevant to the discussion that follows, how does a group of muscles constrained to act as a functional unit maintain its integrity in the face of variations in the nonmuscular forces? The answer, in a sense, has already been given above--the flux of muscular forces is determined by the "design specifications" of the system of muscles--but we have yet to acknowledge the full implications of this answer. If a temporally constrained collection of muscles is an autonomous, self-organizing system then the muscular forces that it generates must be understood as <u>arising</u> from <u>within</u> the collective and not as <u>imposed</u> from <u>without</u>. We have said this before, of course, but the consideration just given to the morphological view of dynamics--geometrodynamics as Wheeler (1962) terms it--permits a more explicit interpretation. In what follows we take a well known demonstration of systematic variation in the fluxes of muscular and nonmuscular force and give it a purely geometric reading. In so doing we provide a way of interpreting discrete, non-oscillatory movements as products of a non-linear oscillatory system.

Asatryan and Fel'dman (1965) and Fel'dman (1966 a,b) showed that the maintenance of joint postures and motions could be understood as the manifestation of an oscillatory device. In particular, they likened the behavior of muscles at a joint to that of a controllable spring system. Briefly, their model construct was a mass-spring system defined by the equation $F = -s_o(l-y_o)$ where F is force, s_o is the stiffness of the spring, l is the length of the spring and y_o is the equlibrium length, that is, the length at which force developed by the spring is zero. This simple mass-spring system is controllable to the degree that the parameters s_o and y_o are adjustable. Changing y_o with s_o constant generates a set of nonintersecting characteristic functions, $F(l) = -s_o(l-y)$, and changing both parameters generates a set of functions $F(l) = s(l-y)$ that will pass through all points in the plane defined by the cartesian product, F x l.

Asatryan and Fel'dman's analysis was based on a <u>qualitative</u> comparison of the geometric properties portrayed in their mechanographic analysis with those geometric properties portrayed by the behavior of a mass-spring system. In essence the analysis was meant to capture the abstract qualitative similarities relating the two systems. The mechanical instantiations of the systems were not of importance. In one case the mechanism was composed of metallic coiled springs and weights with a mechanical forcing component while in the other case the mechanism was composed of nerve and muscle tissue with a metabolic forcing function. What Asatryan and Fel'dman demonstrated was that these two radically different material systems behaved in a "qualitatively" similar manner. Their suggestion was that both systems might be sharing a "common" solution to a dynamic problem. One functional difference between the two systems is that the muscle/tissue system has increased flexibility through the freeing-up of the stiffness and resting-length variables. What we would like to show in the remainder of this section is how to reexamine the Asatryan and Fel'dman plots in such a way that they reveal an underlying organization similar to that of our dynamic model construct.

A first step is to change the plotting convention employed by Asatryan and Fel'dman (see Figure 10). Instead of using a positive/negative convention to distinguish extension/flexion phases of movement, we will plot all moment values with their actual value signs. In other words, if the total moment <u>increases</u> (regardless if it is in the direction of flexion or extension) the value will be plotted in the <u>positive</u> direction. The result of using this convention is a family of curves similar to those plotted in the upper left graph in Figure 9. Recall that that graph depicted a family of nonlinear curves associated with the behavior of a force-driven harmonic oscillator; each curve distinguishes the behavior of an oscillator of a different length, where each length exhibits a different "preferred" (i.e., resonant) frequency. When plotted in their original convention the data of Asatryan and Fel'dman generate a family of linear

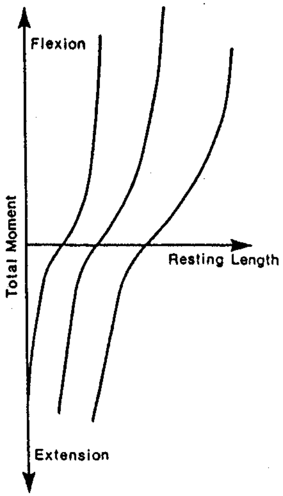

Figure 10

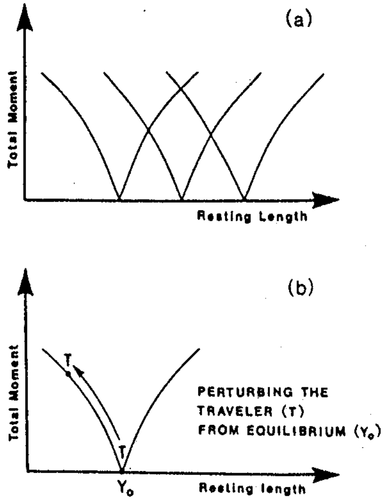

Figure 11

curves as Figure 10 shows. The family of curves in Figure 10 has a geometric profile in which there are no inflection points. For the collection of curves in Figure 10 the appropriate model construct is a linear system. As a member of the class of linear systems there are no regions of preferred stability. When plotted using the alternative convention, however, the data of Asatryan and Fel'dman generate a family of nonlinear curves with a geometric profile that is topologically inhomogeneous, the family of curves in Figure 11a. There are inflection points in the functional organization specifying the system's resting length. For the family of curves that follow from the alternative convention the appropriate model construct is a nonlinear system; there are preferred regions of stability. The geometric profile exhibits an inflection region at the resting length with ascending gradients on both sides. The slopes of these gradients specifies the system's stiffness parameter. (The importance of selecting the "appropriate" plotting convention cannot be over emphasized, for it forms the basis on which the model construct is established. The distinguishing properties are most readily revealed in a geometric analysis of the function's defining topological properties. These are revealed <u>only</u> when the proper plotting convention is used.)

We noted in the previous section that sensitivity to the geometric properties of a function's phase portrait is synonymous to sensitivity to information specific to the underlying dynamic organization of the function. Let us now return to our earlier "traveler" of geometric regions and see how it would behave according to the new "layout" of Asatryan and Fel'dman's data. Suppose an underlying organization of the system is set up such that a given resting length and stiffness is specified. The geometrodynamics associated with this organization is a manifold with a valley specified by the resting length and ascending sloping gradients specifying stiffness. Let us further suppose that the traveler is at rest in the valley. This condition is similar to Asatryan and Fel'dman's condition of the subject maintaining a resting posture. If we now perturb the traveler, by forcing it up one of the sloping walls, the traveler will respond by returning to the valley, which for the traveler represents the region of maximum stability and minimum energy dissipation (Figure 11b). The "rate" (that is acceleration and velocity components) at which the traveler returns will be specified by the steepness of the slope. Thus perturbations to the traveler do not affect the underlying geographic layout but rather displace or relocate the traveler. Once the perturbing influence is removed, the traveler once again tends to return to the stable region in the valley. The information specifying the journey's route is revealed in the geometrodynamics of the surrounding gradients and equilibrium points, where the gradients and equilibrium points are always "scaled" to the dimensions of the system (therefore eliminating any "procedure" of recalibration). Such a style of organization is similar to our earlier discussion of linear and nonlinear systems. Reviewing briefly, linear systems respond to any perturbation by moving to a new location specific to the input perturbation. The mapping function from "input" to "output" for a linear system possesses the defining properties of superposition and proportionality. Put differently, there is a one-to-one mapping relating input to output through some scalar function. Since there are no "preferred" points in the phase portrait, the linear system is free to move to any output region. A perturbed linear system does not have any tendency to return to the state prior to perturbation. In contrast, non-linear systems are characterized by the presence of "preferred" regions in the phase portrait. These points specify regions of maximal stability and minimal energy dissipation. Furthermore, there is a many-to-few mapping function relating input to output such that the system always tends towards "preferred" regions in the output mode. When these systems are perturbed, there is a tendency to return to preferred regions. There is ample evidence to suggest that the style of organization characterizing the maintenance of simple postures is best modeled with a nonlinear system (Asatryan and Fel'dman, 1965; Bizzi, Polit, and Morrasso, 1976; Fel'dman, 1966a,b; Kelso, 1977; see accompanying paper).

16. A Geometrodynamic Perspective on Discrete Movement

Consider now what it means to produce a given movement rather than, more simply, preserving a given posture. Curiously, on the geometrodynamic perspective advanced here, the production of discrete movements is primarily owing to changes in the underlying "geometry" and only secondarily, as a necessary consequence of the geometric change, owing to a change of "forces". A limb in a given posture prior to a discrete single movement means, by the analysis above, that a particular geometrodynamic organization holds over the relevant dimensions. To produce a movement is in effect to change that underlying geometrodynamic organization. This curious thesis is given a hearing through a further consideration of the mechanographic analysis of Asatryan and Fel'dman.

Following Asatryan and Fel'dman, we would argue that while descriptions of movements are generally made in the vocabulary of kinematics (that is, distance, velocity and acceleration) movements are more likely regulated in the vocabulary of dynamics (Fitch & Turvey, 1978). We stated above that a stable postural arrangement could be maintained through the specification of stiffness and resting length parameters. Distance may be regulated through the manipulation of the resting length while velocity and acceleration may be regulated through the manipulation of stiffness. Let us pursue in more detail how this might be accomplished.

Consider our traveler in a resting posture. It finds itself located in a valley specifying its resting length and surrounded by ascending gradients with slope specifying stiffness. By changing the parameter of resting length, while holding stiffness constant, the traveler "suddenly" finds its geographic layout changed (see Figure 12). It is no longer in the bottom of a valley (T), but rather it is now on a sloping gradient (T'), with a new valley off in the distance. This new geographic layout possesses the "new" parameter setting specifying stiffness (in the slope of the gradient) and resting length (in the new location of the valley). Since stiffness has not changed, the slope of the new geographic layout is the same as before the change. In fact, the actual coordinates (s, Y_o) of the traveler's position have not changed, what changed was the geographic layout on which the traveler was positioned. In brief, the traveler's underlying geographic layout was "suddenly" changed by virtue of a reparameterization of the resting length variable. Following the new descending gradients, the traveler once again discovers a stable region in the geographic valley.

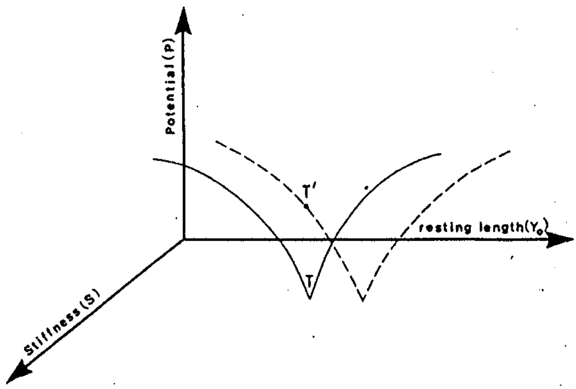

Figure 12

(Read P as a dynamic variable, such as total moment, to which the system is sensitive.)

Consider now the effects of perturbations on the traveler under the changing conditions associated with a simple movement (Figure 13). First, suppose the traveler has its initial conditions changed after the underlying geographic layout has been changed to specify a different location for the valley. In this case, changes in the initial conditions (such as by a momentary perturbation) affect only the traveler's relative position on the underlying geographic layout, they do not affect the geographic layout itself. For example, before a reparameterization occurs the traveler is at rest in a geographic valley (T), suddenly a reparameterization occurs and the traveler discovers that the underlying geographic profile has changed. It is no longer in a valley, instead it is now located on a sloping gradient (T') extending downwards towards a "new valley" (specifying a new resting length). Before the traveler starts its journey, however, a sudden perturbation occurs, forcing the traveler a short distance either up or down the sloping gradient (T"). Put differently, the initial conditions of the traveler's journey have been changed. Importantly the perturbation has no effect on the underlying geographic layout. Therefore, since the geographic layout remains unaltered, the final resting position of the traveler remains the same. Regardless of the nature of the perturbation (within certain limits) the final resting position is invariant. More commonly, such a style of organization is

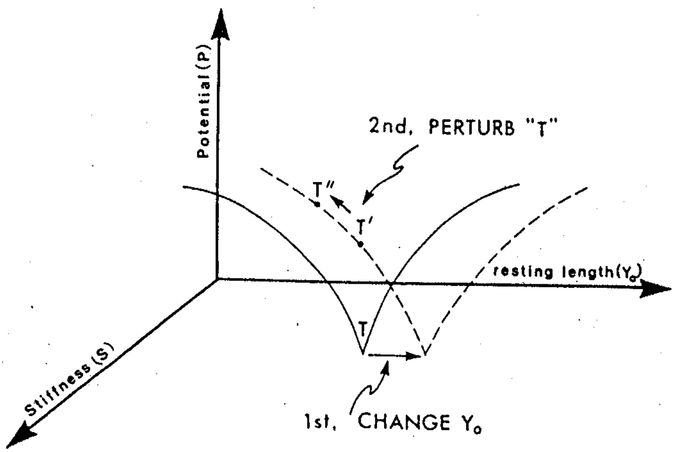

Figure 13

said to possess the property of "equifinality" (that is, the ability to reach the same final condition from various initial conditions). Second, perturbation during the movement similarly only temporarily relocates the traveler. Since the underlying geographic layout is not altered by the perturbation, the traveler again ends its journey in the same final location. Finally, if an external moment is added to the system during the movement, but not removed, then the traveler will end its journey at a resting length deviating from the geographic valley by a distance determined by the external moment and the sloping gradient surrounding the valley (that is, the stiffness parameter). The deviation from the valley is "maintained" by the external moment. As before, the underlying layout is not changed but in this condition the external moment adds a bias to the traveler's disposition, the result being a relative shift in the resting condition predicated upon the biasing nature of the external moment.

Summing briefly, the underlying principle for perturbations is: Perturbations influence the disposition of the traveler but not the underlying geographic layout. When a perturbation is introduced and removed after the underlying geographic parameters have been established and before the end of the movement, then the traveler always ends its journey in the same stable valley region. If, however, a persistent change in the traveler's disposition occurs (such as the addition of a constant external moment), then the final resting location is specific to the underlying geographic layout but now with reference to the traveler's new disposition. Put differently, any change in the traveler's disposition "biases" the final resting location.

From the above arguments the production of discrete movements (and, similarly complex movements) is primarily owing to a change of "geometry," a reparameterization of a geographic layout. A limb in a given posture maintains its postural integrity by virtue of an invariant geometrodynamic organization and movement production is the event consequent to a change in that underlying geometrodynamic organization.

Concluding Remarks

Our efforts in this essay have been directed at defining a model construct in terms of which the control and coordination of movement might be understood. Three related guidelines have shaped the direction taken. First, that the model construct identify a system whose internal degrees of freedom regulate themselves with minimum recourse to an 'intelligent regulator'. Second, that the model construct require a minimum number of design principles, _sui generis_. And finally, that the principles of biological design characterizing the model be mandated by physical principles. In accordance with these guidelines we have suggested that a group of muscles constrained to act as a functional unit, a coordinative structure, is a member of the class of thermodynamic engines _qua_ dissipative structures.

A dissipative structure is a physical system characterized by the ability to autonomously manifest spatio-temporal self-organization. This manifestation requires:

1. A reservoir of potential energy from which (generalized) work can arise.
2. A microcosm of elements with a stochastic fluctuating nature (such as a collective of muscles or at a lesser scale, the fluctuating nature of an interneuronal pool as is manifest in tremor, see accompanying paper).
3. The presence of nonlinear components.
4. A scale change such that a nonlinear component is critically amplified (in the sense that the system's own dimensions now resist the previously dominant effects of the initial and boundary conditions).

If these requirements are met, then the possibility exists for a transition from the stochastic steady-state situation to a spatially structured steady-state situation or a time-dependent, limit cycle regime characterized by homogeneous oscillations or by propagating waves. The regimes are stable, by virtue of the 'amplified nonlinear component', and maintained, by virtue of 'dissipation of energy'. As such the manifestation of these 'open' systems is achieved by drawing spontaneously on potential energy sources at their boundaries. Under these conditions the system feeds on the potential energy source, is stable in the nonlinear sense, and dissipates energy (that is, there is a greater loss of order in the surround than gain of order by the system itself--the behavior of the system is 'lossy' with respect to energy). This behavior is prototypical of thermodynamic engines in that the mean states of the internal variables are characterized by 'fluxes' and 'squirts' of energy that become constrained by nonlinear components so as to behave in a limit cycle manner. The temporal ordering of the 'squirts' is nonspecific (many-to-few mapping) with respect to the stable spatio-temporal structures that are manifest within the system. Thus stable structure, owing to the nonlinear components, may arise and be maintained with minimum specification of internal details. In contrast, for linear components the degrees of freedom captured in the input are conserved (map one-to-one) in the output. Thus structure, owing to linear components, may arise and be maintained but it requires a full complement of detail in the energy 'fluxes' specifying the nature of the arising structure. A dissipative structure is 'well-organized' when it manifests a functional relationship exhibiting properties of both linear and nonlinear components. Under this style of organization, the system reveals qualities of precision and stability. Information specifying linear and nonlinear components, more pragmatically, nonessential and essential components, is made directly available when the system undergoes dynamic transformations. The information is morphological, manifest as gradients and equilibrium points in the system's dynamics. If the information specifies only nonlinear components then the system is stable in the face of perturbations to the point of prohibiting (useful) variation; if, on the contrary, the information specifies only linear components, then the system is variable in the face of perturbation to the point of indifference with respect to stability. In sum, pragmatic coordination <u>and</u> control is realized only when the information specifies sources of stability <u>and</u> precision, respectively.

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