378

The Development of Movement Control and Co-ordination
Edited by J. A. S. Kelso and J. E. Clark

CHAPTER 1

On the Control and Co-ordination of Naturally Developing Systems

P. N. KUGLER, J. A. SCOTT KELSO, AND M. T. TURVEY

INTRODUCTION

The purpose of this chapter is to present and to discuss certain principles as a backdrop for the thesis that an understanding of the developmental facts of movement control and co-ordination requires a physical (rather than a formal) approach carefully tempered by a realist (rather than a nonrealist) philosophical attitude. Our presentation and discussion are largely in the tutorial mode because the principles are not commonplace departure points for students of the development of movement. The principles are drawn from philosophy, biology, engineering science and, in particular, nonequilibrium thermodynamics and the ecological approach to perception and action. Throughout, our paradigm issue is an aspect of the larger developmental picture, namely, the implications of a scaling-up in the body's magnitudes for the control and co-ordination of movement. And within the scope of this latter issue our concentration is on the notion of information: how can information be conceptualized so that it is continuously co-ordinated with changes in skeletomuscular dynamics that are brought about by changes in skeletomuscular dimensions?

1 PRELIMINARY REMARKS: DEGREES OF FREEDOM AND THE PRINCIPLE OF SIMILITUDE

An attractive view of the movements of animals is one that treats movement as form, as an adjacent and successive ordering of the body's skeletal linkages, and which, therefore, aligns the study of movement production and of the changes in movement that accompany growth with the more general study of morphogenesis. Troland (1929, pp. 366–367), some fifty years ago, subscribed to a formational view of movement; for him, movements were 'ordered successions of progressively different postures.' A posture of the skeleton, like the form of any portion of matter, is to be described as due to the action of forces. In D'Arcy Thompson's (1917) terms, the form of an object – here a movement of the body – is a 'diagram of forces' in that one could, in principle, deduce from it the forces currently and previously in action. Skeletal poses progressively transformed are, of course, less analogous to solid objects than they are to fluids; they are varying rather than frozen forms, but they are, all the same, the resultant of a configuration of forces that index the manifestation of various energy kinds.

1.1 Movement as a 'Diagram' of Muscular and Nonmuscular Forces Drawn on Many Degrees of Freedom

It was, perhaps, Bernstein (1967) who first gave full emphasis to the totality of forces in interpreting the 'construction' of movements. For Bernstein, to focus on those forces due to muscular contraction was insufficient. A viable account of movement had to include, with equal emphasis, inertia and reactive forces – those that result from motions of the body and those that result from mechanical contact with surfaces and media. (See Gibson's (1979) definitions of these terms and see Hertel's (1966) discussion of flying and swimming.) A movement of the human body, therefore, is a 'diagram' of muscular *and* non-muscular forces and it is, as we will express it below, a diagram drawn over a large number of degrees of freedom.

The human body (in childhood and in maturity) has in the order of 792 muscles that act, rarely singly and almost always in combination, to generate and degenerate kinetic energy in over 100 mobile joints (Wells, 1976). These joints vary in the kinds of anatomical pieces that they link (cartilages, bones) and in the number of axes over which they can change (for example, hinge joints like the elbow are uniaxial whereas ball-and-socket joints like the hip are triaxial). Were we to take a conservative stance on the body's mechanical degrees of freedom, one that assumed the existence of only hinge joints, we would still be facing a system of 100 or so mechanical degrees of freedom (see Turvey, Fitch, and Tuller, in press).

The organizational principles of movement, subsumed by the general (and unevenly interpreted) terms 'control' and 'co-ordination,' realize behaviors of very few degrees of freedom from a skeletal basis of very many degrees of freedom; they define a mapping from a space of multiple fine-grained variables to a space of considerably fewer coarse-grained variables. To put it most bluntly, the organizational principles of movement systematically dissipate degrees of freedom.

One can take a perspective on the largeness of the body's number of mechanical degrees of freedom that regards it as a 'problem' (e.g. Bernstein, 1967; Gelfand *et al.*, 1971; Greene, 1972; Turvey, 1977) and the aforementioned principles as the 'solution'. This perspective identifies the articulation of the 'solution' to the 'problem' as the foremost task of movement science. It will be a central theme of the present chapter that candidate solutions cannot be indifferent to the facts of growth as expressed by the Principle of Similitude.

1.2 The Principle of Similitude or Dynamical Similarity

It has long been respected that the limiting condition on the actions and forms of terrestrial creatures is the strength of the earth's gravity: the forms that animals take are proportional to gravity's pull. Imagine a doubling in the magnitude of gravity: the upright posture that marks *homo sapiens* would be rendered inoperative, and the largest inhabitants of the earth would be reduced to short-legged creatures with bodies very close to the ground or to legless, snakelike creatures with bodies in contact with the ground. In contrast, a halving of gravity's strength would yield tall and slender creatures requiring less by way of energy and equipped with metabolic organs – heart, lungs, etc. – of comparatively diminutive size. That form would change proportionately with gravity is one manifestation of the Principle of Similitude or Dynamical Similarity (see Bridgeman, 1922; Thompson, 1917/1941). A further and reciprocal manifestation of the Principle – one that is less demanding of the imagination – is that form changes proportionately with size.

The forces which determine an organism's form vary, some as one power and some as another power of the organism's dimensions such as, for example, its height or its length. That is to say, forces do not configure independently of dimensions: a scale change in the dimensions is accompanied by a change in the relative values of the forces. Necessarily, form as a diagram of forces changes with a change in scale.

To illustrate, suppose that an engineer, after constructing a strong and durable bridge was then confronted by the problem of building a much larger bridge. To save time, the engineer repeated the earlier design by simply applying a scale factor to the bridge's linear dimensions (such as the lengths of its struts and girders). Unfortunately, this new, larger bridge, though geometrically identical to its smaller counterpart, could never match its stability. The resistance of a supporting structure to a crushing stress – its strength, if you wish – varies as the square of a linear dimension (say, its length) whereas the weight of the structure varies as the cube; thus the larger of the two geometrically similar bridges is disproportionately heavier for its strength and is, therefore, more prone to collapse. Though the set of dimensions is the same for the two bridges the difference in scale is accompanied by a difference in the configuration of forces. At the smaller scale the geometric form represents a stable configuration of forces whereas at the larger scale that same form, in terms of forces, is configurationally unstable. Stability of forces at the larger scale necessitates a change in the geometric form.

By these various considerations changes of form, however inappreciable to the eye, will occur as long as growth lasts. This is one lesson to be learned from the Principle of Similitude or Dynamical Similarity. An equally significant lesson for our present purposes follows from considering not the dynamical differences between geometrically similar systems that may accompany a change in scale, but the dynamical *sameness* of geometrically similar systems that may persist over a change in scale. That is, we need to consider the case in which two systems do not distinguish qualitatively though they may distinguish quantitatively.

Suppose that we were investigating a physical process known to depend on an identifiable number of measurable attributes or dimensions. (And in the following we paraphrase Rosen's (1978) development of this topic.) The process can be lawfully described as some functional relation among the dimensions here designated by x_i:

$$\phi(x_4 \ldots x_n) = 0 \tag{1}$$

Assuming that the process is defined on a mechanical system, we can take mass (M), length (L) and time (T) as the fundamental dimensions (identified, for simplicity, with x_1, x_2, and x_3) in terms of which the other dimensions (x_4 through x_n) of (1) can be described. For example, if frequency, velocity, and force were three of the 'nonfundamental' or derived dimensions then they would be expressed as T^{-1}, L/T and ML/T^2, respectively (see Stahl, 1962). More generally any derived dimension in (1) (that is, $x_4 \ldots x_n$) would be given by:

$$x_i = M^{\alpha_i} L^{\beta_i} T^{\gamma_i} \tag{2}$$

If now we rewrite (2) as a ratio:

$$\pi_i = x_i M^{-\alpha_i} L^{-\beta_i} T^{-\gamma_i} \tag{3}$$

it is readily recognized that π_i is *dimensionless* – it is a *pure* number. It follows that (1) can now be rewritten in dimensionless form;

$$\phi(\pi_4 \ldots \pi_n) = 0 \tag{4}$$

Suppose that we now wish to compare a second process ϕ' with ϕ where ϕ' like ϕ is describable by (1) but where ϕ' differs from ϕ in terms of the values of the observables, x_i. Putting each process into the dimensionless form of (4) allows for a determination of their dynamical similarity; precisely, ϕ and ϕ' are similar if and only if the dimensionless quantities π_i, π'_i are respectively equal. With respect to the two bridges referred to above: their measurable attributes or dimensions are the same but they differ in scale; that they also differ in stability would be interpretable, by the preceding formulation of the Principle of Similitude, as due to the fact that their respective dimensionless numbers are not equal.

We have remarked that in the interests of stability the larger bridge would have to assume a form different from that of the smaller bridge. But it is perhaps intrinsically obvious that there should be a range of magnitudes over which the two bridges could differ yet remain dynamically similar and, therefore, equally stable. That is to say, the dimensionless numbers in their respective equations should remain virtually equal up to some difference in scale. That scale value at which the two bridges can no longer be related by a similarity transformation – that is, the larger must assume a form different from the smaller – is referred to as a *critical value*. The general notion of critical scale values will figure significantly in the discussions that follow. A dimensional analysis of the damped harmonic oscillator will help to clarify the notion; in addition it gives a concrete example of the procedure for arriving at equations in dimensionless form.

The differential equation of a harmonic oscillator with mass m, damping B, and stiffness k is:

$$m\ddot{x} + B\dot{x} + kx = 0 \tag{5}$$

From the general solution to this equation the frequency f is given by

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m} - \frac{B^2}{4m^2}} \tag{6}$$

That is to say, there is a basic equation of the form

$$\phi(f, B, m, k) = 0 \tag{7}$$

Taking m and (for simplicity) k as the fundamental dimensions then the derived quantities f and B may be expressed, respectively, as

$$f = k^{1/2}m^{-1/2}, \quad B = m^{1/2}k^{1/2} \tag{8}$$

giving rise to two dimensionless quantities

$$\pi_1 = m^{1/2}K^{-1/2}f, \quad \pi_2 = m^{-1/2}K^{-1/2}B \tag{9}$$

and the dimensionless equation

$$\phi(\pi_1, \pi_2) = 0$$

Let us now see what happens when B, described dimensionally, takes on the value $2m^{1/2}k^{1/2}$. This value of B substituted into (6) renders the quantity under the radical equal to zero which is synonymous with driving f to zero. In short, $B = 2m^{1/2}k^{1/2}$ is a critical value associated with a dramatic qualitative change in the behavior of the system described by (5): below this critical value the system oscillates; at and above this critical value it does not.

Let us now relate these remarks on similitude (that two physical processes with common dimensions related by a common function are dynamically *similar* up to some scale value) and 'dissimilitude' (that two physical processes with common dimensions related by a common function are dynamically *dissimilar* beyond some scale value) to the control and co-ordination of movement.

1.3 Implications of the Principle of Similitude for the Theory of Co-ordination and Control

The Principle of Similitude is most frequently discussed with reference to biological functions – to goal-directed activities or *effectivities*. A particular bodily form, anatomical structure or physiological arrangement serves as a 'method' for realizing a given effectivity only up to some limiting magnitude of a linear dimension. Beyond that magnitude the 'method' for realizing the same effectivity will have to change. To illustrate, most animals rely on aerobic metabolism and therefore are designed so as to guarantee that their tissues are supplied with adequate amounts of oxygen. The method by which oxygen is transported to tissue is scale-dependent. For the smallest of animals – from protozoa to the flatworm – oxygen transport is solely by diffusion on gradients of partial pressure. However, beyond a tissue thickness of approximately 0.06 cm (Alexander, 1968) this method of transporting oxygen is unworkable and some other method has to be used; for a large number of animals it is the circulation of blood infused with respiratory pigment.

There are two ways in which the magnitudes of a person's bodily dimensions change. They change naturally as an accompaniment of age and they change artificially – for example, as a matter of wielding and carrying objects. By virtue of the Principle of Similitude alone we should expect that as a child grows bigger an effectivity such as walking or throwing will pass through a sequence of qualitatively distinguishable forms, where each form is stable over a limited range of growth in the bodily dimensions. We do not wish to be read here as saying that the simple scaling-up of a linear dimension is responsible for the developmental pattern that is actually observed in walking and throwing (see, respectively, Bernstein, 1967; Roberton, 1978) rather that a scale change is sufficient to induce a sequence of distinguishable stable and unstable movement patterns for the same effectivity. Similarly, by virtue of the Principle of Similitude alone we should necessarily expect that an effectivity supported by skeletomuscular motions will be either subtly or radically modified by 'artificial' magnitude changes in the fundamental dimensions of mass, length, and time wrought by the implements struck with, the missiles thrown, the loads carried, the surfaces walked, run, and stood upon, etc. The child who exhibits a free, natural sidearm swing with a lightweight striking implement transfers to an arm-dominated push at the ball when required to hit with a heavier instrument (Halverson, Roberton, and Harper, 1973).

Whether they be introduced naturally or artificially, increases in the lengths and masses of biokinematic links must be accompanied by changes both in the muscular forces needed to initiate and arrest the motions of the links and in the reactive forces that the links generate in starting, moving, and stopping. This means that a given movement pattern which remains relatively invariant over a period of growth or over an artificial scaling up of dimensions cannot be the result of constant forces generated at fixed times; put differently, the 'diagram of forces' – the form of the movement – remains unchanged although the actual quantities of the forces, muscular and nonmuscular, and their timing do not. Formally speaking, this situation of a constant movement pattern over inconstant magnitudes is analogous to the invariance described above in which two processes defined in the same way over the same set of dimensions are dynamically similar – for nonidentical values of these dimensions – when their respective dimensionless numbers are equal. Physically speaking, this situation of a constant movement pattern over inconstant magnitudes necessitates a principled basis for determining the muscular forces which, together with the circumstantially determined nonmuscular forces, configure to give the constant movement pattern. The related situation – of a qualitative change in a movement pattern at critical magnitudes of one or more dimensions – necessitates a principled basis (i) for determining that at a certain magnitude a given movement pattern, a given diagram of forces, is no longer supportive of a given effectivity; and (ii) for selecting the new movement pattern (or patterns) appropriate conjointly to the dimensional magnitudes and the effectivity. These two cognate desiderata (of accounting in a principled fashion for the scale-associated qualitative invariants and qualitative changes in patterns of movement) identify the restriction on the solution to the problem of degrees of freedom that is imposed by the Principle of Similitude. More generally, they identify a restriction on the solution to the problem of how movements are co-ordinated and controlled in a system whose dimensions change in magnitude, regardless of whether the changes are abrupt or gradual.

Two frequently promoted conceptions for understanding control and co-ordination are the motor program (e.g. Keele and Summers, 1976; Keele, 1980) and the schema (e.g. Pew, 1974; Schmidt, 1975; see Shapiro and Schmidt, this volume). These conceptions derive in large part – as we will argue in Section 1.4 – from a particular perspective on biological order. With respect to the task of satisfying the above desiderata of the Principle of Similitude, we ask whether conceptions such as motor program and schema are sufficient and whether they are necessary.

Suppose the ability of a child at age t to strike a ball through a particular movement pattern m was owing to a motor program p. And allow that a motor program, roughly speaking, is a detailed set of instructions to contract such and such muscles, to such and such degrees at such and such times (but see Keele, 1980 for a different definition). At some later age, say $t + 1$, the child's muscles are of greater cross-sectional area and the child's bones are of greater length and mass in comparison to their magnitudes at t. To produce the same movement pattern at $t + 1$ the child cannot rely on the coded instructions used at t for they are not referential of the current set of skeletomuscular magnitudes. Of course it is generally conceded that motor programs operate with a skeletomuscular context that is not necessarily fixed and therefore programs must be adaptable within reasonable limits. The adjustments to the program's coded instructions are said to be based on feedback, that is, information about the skeletomuscular states of affairs. Under the feedback proviso the program's subgoals or reference signals – roughly of the sentential form 'get this trajectory from this joint at this point in time' – remain the same, just the signals to the musculature change. Though a great deal of unpacking has to be done to make this feedback formulation work, even when relatively few degrees of freedom are involved (Fowler and Turvey 1978; Gelfand and Tsetlin, 1962), we can allow, for sake of argument, that it is tractable. This latter concession is made ungrudgingly because we wish to parlay the double-duty performed by the information about the skeletomuscular states of affairs into a denial of the sufficiency of the program and schema conceptions. What are the two duties?

At age $t + 1$ the child's dimensions had not exceeded a value at which movement pattern m was unreliable. Within the period t to $t + 1$ the aforementioned information is termed 'feedback' and is assimilated to p's referent signals. But now suppose that at $t + 2$ the child's dimensions have magnified critically – m is no longer tenable and a new, qualitatively different movement pattern is required. Within the period $t + 1$ to $t + 2$ the aforementioned information is not just data to be assimilated to p but it is data to be accommodated by p – in short, it is now also 'feedforward' that specifies new subgoals, new referent signals and hence, a new program. What is lacking in the motor program and schema conceptions is any *principled* account of how information about the skeletomuscular states of affairs can do double duty as feedback and feedforward. Without such a principled account these conceptions are insufficient to satisfy the above desiderata. Let us now ask whether they are necessary.

A most obvious response to the double-duty observation is to pursue further the conceptions of program and schema; under some possible elaboration a principled account may be forthcoming. The success of this response cannot be dismissed offhand though we confess to being skeptical and give expression to this skepticism in various sections of the chapter. For present purposes it suffices to note that countenancing an elaboration of the program and schema conceptions with regard to the above desiderata is tantamount to disavowing the continuity of similitude and dissimilitude effects in animal movement and other natural domains. While we should suppose that the worked-through physical account of these effects is most general, the tack of pursuing the program and schema conceptions would have us abandon that generality when animal movements are the object of study and espouse instead explanatory principles of a new and special kind.

The notions of programmed instructions and schemas can have no role in explanations of, say, the forms assumed by water or air as the magnitudes of certain dimensions vary. Nevertheless, one might wish to claim that these notions can have a role in the explanation of scale-associated effects in animal actions. It is doubtful, however, that they can have a *necessary* role in such explanations. The understanding of nature tends to progress through the identifying and gradual extension of very general explanatory principles that accommodate the particular and the novel rather than through the proposing and pursuing of particular and novel explanatory principles *sui generis*. A measure of this latter assertion is to be found in the section that follows. We conclude the present section by noting that if there were some very general physical account of scale-associated invariants of form and changes of form then to that account we should turn for insights into the problem of degrees of freedom in movement and into a conception of the informational basis for movement that is continuously co-ordinate with scale.

1.4 Contrasting Perspectives on Order and Regularity

An understanding of the systematic regulation of the body's many degrees of freedom can be sought from two perspectives that are often in opposition where matters of order and regulation in biology are at issue. One perspective (and in many respects the more popular of the two) equates the aforementioned understanding with the resolution of the technical or engineering problem of how, given a multivariable mechanical system, one could effectively control its behavior. In this 'artifactual' perspective: (i) the body's many degrees of freedom are a 'curse' (cf. Bellman, 1961) or a 'problem' (cf. Turvey, 1977); (ii) co-ordination and control are impositions on the skeletomuscular apparatus; and, relatedly, (iii) the central nervous system as the putative source of the co-ordinating and controlling signals is sharply distinguished from the high-powered, energy-converting skeletomuscular system that is the putative recipient of those signals.

Not unexpectedly the artifactual perspective promotes contemporary manmade machines as model sources of ideas for understanding how the degrees of freedom of the body are co-ordinated and controlled. The major candidates are machines in which control is effected through a pre-established arrangement among component parts (here termed 'cybernetic machines') and machines in which control is effected through a pre-established arrangement among specific instructions (here termed 'algorithmic machines').

The artifactual or machine conception (see von Bertalanffy, 1973; Kohler, 1969) has assumed in recent decades an unprecedented status as *the* perspective on order and regulation. This has been owing, in very large part, to the fact that the development of automata theory, information theory, and cybernetics has made secure the concept of machine in ways that appear on *prima facie* grounds to be of special relevance to the 'puzzles' of biology and psychology (see Berlinski, 1976). In automata theory the abstract mathematical notion of a machine was given an explicit reading by tying it to both recursive function theory and the digital computer. By this explicit reading, recalcitrant natural phenomena – such as the cognitive abilities of humans – could be viewed as analogous to machine capabilities and explainable in machine terms (Fodor, 1975; Minsky and Papert, 1972; Pylyshyn, 1980). The formal conception of information, as expressed by Shannon and Weaver (1949), gave a precise and mathematical way of describing communication situations. Moreover, the way in which information theory linked information with probability and with the physical concept of entropy gave it an air of great generality – a theory adaptable, in principle, to many systems and to many phenomena. Thus, in biology the egg-to-organism link could be likened to a communication channel; in principle, the information stored in the egg's nucleus, cytoplasm, and cortex that is eventually transmitted could be estimated (Elsasser, 1958; Raven, 1961). In psychology, stimuli, in principle, could be quantified for their information content and the perceiver's efficacy as a transmission channel, in principle, could be calculated (Attneave, 1959). The fixing of a biologically and psychologically useful conception of machine by automata theory and information theory was abetted by cybernetics which provided an understanding of machine behavior as goal-directed. Thus in biology and psychology the cybernetical closed-loop device that includes a constant reference input (the goal) and negative feedback is a commonplace explanation of conserved values (e.g. Adams, 1971; Powers, 1973, 1978; Riggs, 1970).

Despite the great popularity of the artifactual or machine perspective on order and regularity there are (we believe) good reasons to question its appropriateness. In subsequent sections arguments will be given against the propriety of formal automata theory and classical information theory for understanding motor development. It suffices for the present to question the propriety of the cybernetical closed-loop device for explaining relative stability in biology.

If it is claimed that an output variable of a system is relatively constant – for example, body temperature, respiratory frequency – because of the presence of a constant reference signal then is it not necessary to inquire, further, how it is that the constancy of the reference signal is assured? An infinite regress is enjoined if the latter question is answered – as surely it must be – by an appeal to another negative feedback system which has as its output the previously referred to referent signal and as its input another constant reference signal; for now a further negative feedback machine must be proposed to assure the constancy of this additional, higher order referent. A much better claim – or so we and others (e.g. Yates, 1981; Werner, 1977) would argue – is that any relative constancy in biological systems is an *emergent* and *distributed* property (a steady-state operating point) of physical processes. These processes are sometimes describable by a set of coupled equations whose various parameters, differentially weighted, contribute to achieving the constancy. With regard to temperature regulation Werner (1977) argues that heat flow equations must be calculated for all local co-ordinates; for all parts of the body the characteristic functions are to be found describing (i) metabolism's dependence on heat inflow and (ii) heat outflow's dependence on metabolism. Functions of type (i) are of negative slope while those of type (ii) are of positive slope. For a given body part the only steady-state possible – the only temperature – is that point which is mutual to the two characteristic functions. The gist of Werner's (1977) analysis is shared by Mitchell, Snellen, and Atkins (1970): so-called core temperature is an *a posteriori* fact not an *a priori* prescription.

Zavelishin and Tenenbaum (1968) provide an elegant empirical demonstration that the relative constancy of a given respiratory parameter may best be conceived as an *a posteriori* emergent fact of distributed, paired physical processes with opposite slopes in the relationships between their state variables. Zavelishin and Tenenbaum (1968) first determined the characteristic function relating the duration of inspiration (D) to the resistance to inspiration (R): $D = f_1(R)$. An artificial feedback relation was then imposed between D and R: $R = f_2(D)$. Following the introduction of the artificial feedback link the duration of inspiration underwent variation – driven by the coupled equations – until it achieved a steady state (or steady states) represented by the point (or points) mutual to $D = f_1(R)$ and $R = f_2(D)$.

Further considerations underscore our impression that the negative feedback device with constant reference input has been overvalued. As an example of regulation, the steam escape valve on a common kitchen pressure cooker can be formally analyzed in terms of feedback, referent signal, comparison, etc. Yet to take these terms seriously would be a mistake; they do not stand for anything explicit (Yates, 1980). The regulation band of the pressure cooker is determined by its various parameters (for example, the weight of its stop valve) just as the equilibrium point of a simple mass-spring system is determined by the parameters of mass, stiffness, and friction. To impute to a mass-spring system a reference signal, a feedback loop, a comparator, an error-correcting device and the like would be to impute fictitious entities (Fowler *et al.*, 1980; Kelso *et al.*, 1980; Kugler and Turvey, 1979).

At the heart of these latter considerations is the constrast between order (specifically, an index of stability such as the value of body temperature) as an *a priori* explicit prescription that exists independent of and *causally antecedent* to the dynamical behavior of a system and order as an *a posteriori* fact that arises dependent on and *adjunctively consequent* to (see Shaw and McIntyre, 1974; Turvey and Shaw, 1979) the dynamical behavior of a system. This contrast flags an entry point into the other perspective on order and regulation. In this other perspective, which can be termed 'natural,' the focus is order as a (necessary) *a posteriori* fact. We will make the eccentric claim that the natural perspective is grounded in two necessarily coupled themes: *The proprietary (explanatory) principles of physical theory, with their underscoring of* *tendencies in dynamics, and the proprietary (ontological and epistemological) tenets of ecological realism.* Because it is the natural (rather than the artifactual) perspective that we take to be proper for the present concerns – viz., moving towards a solution to the problem of degrees of freedom that is consonant with the facts of growth – a large part of what follows is devoted to spelling out in some detail what the two coupled themes of this perspective entail. Initially however, our focus is the artifactual perspective, particularly the concept of information that it inspires.

2 INFORMATION AND GROWTH: THE ARTIFACTUAL PERSPECTIVE

The issues raised in Section 1.2 can be reworded as follows: how can the body's degrees of freedom be consistently regulated when the magnitude of the body's dimensions change naturally and artifically? Or, what is the informational base for systematically constraining the body's degrees of freedom and how is that informational base co-ordinated with changes in the body's dimensions?

The artifactual perspective encourages a view of the central nervous system as logically distinct from the skeleton and the musculature. According to this dualism the central nervous system is the source of the signals that inform the skeletomuscular dynamics and it is the site of the information on which such signals are based. If the cybernetical machine is the model then the signals controlling skeletomuscular dynamics derive from reference values or set points; if the algorithmic machine is the model then the signals controlling skeletomuscular dynamics derive from stored rules or programs. In the present section we identify an influential argument for holding information and dynamics distinct; and we consider two generalized conceptions of information that are popular in the artifactual perspective – the linguistic conception and the information theoretic conception – in terms of their relevance to the questions posed above. To anticipate, we express reservations about some steps in the argument and about the general propriety of these two characteristics of information.

2.1 The Complementarity of Information and Dynamics

Pattee (1977) provides a view of autonomous complex systems as operating in two complementary modes, the dynamical and the informational or linguistic modes. While there is more than one reading to be given to complementarity there is a potentially significant reading with regard to our present purposes that should be underscored, viz., that the complementarity of information and dynamics is a design requirement of complex systems (Rosen, 1973; Pattee, 1977). This reading is intended to contrast with an interpretation that is commonly ascribed to the complementarity principle in quantum mechanics – that complementarity, continuous as it is with the uncertainty principle, follows from, and gives name to, a technical impossibility. (In standard terms, that of at once precisely locating the position and measuring the velocity of an elementary particle.) The point underscored here is that, with regard to the science of complex systems, the putative complementarity of information and dynamics is seen not as a methodological failing but as an ontological fact.

The reasoning behind the complementarity of informational and dynamical modes is roughly as follows (see Pattee, 1972a, b, 1973, 1977):

1. The microscopic degrees of freedom of all systems, inanimate and animate, abide by the laws of motion and change, that is, dynamical laws.
2. To harness these laws to produce specific and reliable macroscopic functions requires constraints which selectively reduce degrees of freedom.
3. Constraints with relaxation times that are relatively long in comparison to the phenomena of interest may be termed structural: they are said permanently to freeze-out degrees of freedom. Constraints with relaxation times that are relatively short in comparison to the phenomena of interest may be termed functional: they are said effectively to select one trajectory from among the virtual trajectories that a system might exhibit. The latter type of constraint is a control constraint and it is the one of major interest.
4. Unlike the dynamical laws which are expressible as functions of rate, i.e. as derivatives of some variable with respect to time, the constraints that harness these laws are rate-independent. This is the fundamental incompatibility of laws and constraints qua rules.
5. Constraints are unlike dynamical laws in two other ways: they must have a specific material embodiment (laws are incorporeal) and they are local (laws are universal).
6. Because the microscopic degrees of freedom of the physical embodiment of a constraint must abide by the laws of dynamics, the details of their individual motions must be completely determined. Therefore, the only sensible interpretation of a constraint is that it is an alternative description of the behavior of the individual degrees of freedom.
7. Synonymously, a constraint is a classification of the microscopic degrees of freedom; it is a reduced, less detailed description. Being less detailed it is less complex and therein lies its utility: in terms of control a constraint is simple and efficient because it makes the fullest use of the dynamical context without being a description of that context.
8. Constraints are not only extremely simple with respect to the dynamics that they control but the structure of their physical embodiment has no

direct relationship to those dynamics just as the structure of a written injunction (say, STOP) has no direct relationship to the structure of the activities that it might be associated with. Constraints are therefore like symbols – they are arbitrary with respect to that which they signify.

9. Being arbitrary and just symbol vehicles, individual control constraints assume definite meaning only in the context of a system of constraints. This is tantamount to saying that a co-ordination of symbols – a generalized language structure or syntax – defines the informational basis for the control of dynamical processes.
10. There are, therefore, two descriptions of a complex system. One description is of the system's states of affairs as infinite, continuous and rate-dependent (the dynamical description) and the other description is of the system's states of affairs as finite, discrete and rate-independent (the informational or linguistic description). These two descriptions are incompatible but complementary.

2.2 The (quasi) Linguistic View of Information

There are two features of the foregoing argument on which we wish to focus: (i) that the proprietary conception of information is (quasi) linguistic; and (ii) that the linguistic mode and the dynamical mode, information and action, are arbitrarily related and logically independent in the significant sense that the structure of either one does not determine (or only weakly determines) the structure of the other.

We may suppose, therefore, from the artifactual perspective that the information base for the control and co-ordination of movement is a language of some kind; and pursuing the questions which introduced this section we can ask whether (given feature (ii) above) the information base so construed can change co-ordinately with changes in skeletomuscular dynamics wrought by changes in the magnitudes of skeletomuscular dimensions. While a definitive answer is not possible, there are strong hints that the answer, when forthcoming, will be negative.

Consider the issue of self-complexing (Apter, 1966): can an information base that is conceived as an internal language become richer in the course of development in the sense that qualitatively distinct predicate types can be added? For the newborn infant to behave any way other than convulsively means that constraints are present at the outset and, as we saw from the argument of 2.1 above, constraints are interpretable as symbols co-ordinated by a grammar. That is, constraints, in the above view, constitute an internal language understood at the very least as a representational medium of predicates and their extensions. If the central nervous system (as the information base and source of controlling signals) and the high-powered, energy-converting skeletomuscular apparatus (as the dynamics to be controlled) are logically independent then some procedure is needed to mediate or co-ordinate the two; the information base must be apprised of the dynamical details of movement. In so far as the dualism of central nervous system and skeletomuscular system is a variant of the dualism of animal and environment (see Turvey and Shaw, 1979 and 4.1 below) then we might expect that procedures logically equivalent to those proposed to mediate an animal's perception of its environment can be proposed to mediate the body's (qua central nervous system) perception of its dynamics (qua activities of the skeletomuscular system). This line of argument suggests that the procedure mediating information base and dynamics is most likely a form of projecting and evaluating hypotheses, for that has been the most popular and the most generally agreed upon contention (e.g. Fodor, 1975; Gregory, 1974; Helmholtz, 1925; Rock, 1975).

It can be ably argued however (e.g. Fodor, 1975) that a hypothesis-testing procedure *cannot give rise to new predicate types*. The general argument, roughly speaking, is that any system whose present competence is defined by a 'logic' of a certain representational power cannot progress, *through the mediary of formal logical operations* (such as forming and evaluating hypotheses), to a higher degree of competence. A hypothesis is a logical formula as is the evidence for its evaluation, and both formulae must be couched in the predicates of the system's internal language. Thus an informational base construed linguistically is closed to complexity; it cannot increase its expressive power, that is, it cannot come to represent more dynamical states of affairs than it can currently represent although it can come to mark off those dynamical states of affairs that do in fact obtain from those that do not.

We see, in short, that information construed linguistically can change coordinately with dynamical states of affairs under the condition that the language's power to characterize dynamical states of affairs always encompasses whatever (pragmatically relevant) states of affairs might arise. If it is the case that the set of dynamical states of affairs is open to complexity, unlike the information base, then it will be necessary to include in the information base predicates that are of no use in the present but will be of use in the future. That is, the information base will have to exhibit preadaptive foresight; it will have to include predicates to be used for representing dynamical states of affairs (of a higher order complexity) that are not yet extant.

By way of summary, we have given consideration to the construal of information as language-like and as logically independent from dynamics, and we have looked to the information base and the logical operations that feed upon it as the primary mechanism of development. The upshot of the argument sketched above is that under the foregoing construal of information, the order of complexity a system can achieve is determined by, and identical with the order of complexity with which it began.

2.3 The Information-Theoretic View of Information

How fares the classical interpretation of information (Shannon and Weaver, 1949) when extended beyond the narrow problems of communication channels (for which it was designed) to issues of growth and development? A basic result of information theory is that in a closed system in which nothing enters from the surrounding medium – that is, a communication system of source, channel, and receiver that is secured against extraneous signals – the information content of the receiver cannot exceed that of the source. Information (in the information theory sense) cannot be gained. It is true, of course, that information (in the information theory sense) can be changed, as the dots and dashes of the Morse code can be transcribed into the letters of the alphabet. But, importantly, there is change neither in the quantity of the information nor in what it signifies.

Consider a notorious application of the information-theoretic view of information to biology. Raven's (1961) theory of oogenesis addresses the relationship between generations of organisms that are connected by sexual reproduction; to be more precise, it addresses the fact that the ordered structure of the parents is repeated in their offspring. The basic assumption of Raven's theory is that the orderly spatiotemporal patterns, in terms of which the elementary parts and processes are configured from one generation to the next, are based on a transmission of detailed information conventionally measured in *bits*. In such a communication system the sex cells and the fertilized egg cell produced by their union are parts of the communication channel; the parents are the source and the individual arising from the egg is the destination of the information transmitted. Considered in these terms the formation of the egg involves the encoding of information, and development is essentially a process in which this information is decoded. In short, the ordered structure, the encoded pattern of the fertilized egg, faithfully represents specific information concerning the morphology of the organism that develops from the egg. Oogenesis, therefore, advocates a strong preformationist claim that the information content of the mature organism must be wholly contained in the chemical structure of the genes – it is extracted during growth to guide the dynamics of morphogenesis.

This general thesis, that the development of organismic form (the emergence of phenotype from genotype) is *not* a gain of information, seems intuitively nonsensical to most (e.g. Waddington, 1968) and constitutes one good motivation for the abandonment by biology of the information-theoretic view of information (at least its quantitative aspects, see MacKay, 1969). Other reasons for the abandonment of the classical view of information that should be advanced follow from the mathematical and physical origins of the theory. Mathematically speaking, information theory is part of statistics and its concerns are primarily those of quantities and degrees of certainty. With regard to some state of affairs, an information-theoretic analysis reports on what that state of affairs is not, but might have been (cf. Gibson, 1966). Information in the information-theoretic sense reduces uncertainty – it is a metric by which a state of affairs p is distinguished from other possible states of affairs, say, q and r; it is not, however, and most importantly, a metric by which a state of affairs p is specified. *In a closed system where the possible states of affairs are fixed and given* a priori, *the criterion of distinguishing is sufficient for a conception of information. In an open system where new states of affairs arise a criterion of specifying rather than discriminating must be pursued.*

In a similar vein, information theory's physical origins are not those of a potentially successful physical biology. Information theory is based on equilibrium-reversible thermodynamics, a physical theory which is mute on (indeed, without significant qualifications, contrary to) the facts of growth and development (see 3.0 below). Information as classically construed by Shannon and Weaver (1949) is a measure of probability in the terms of 'deviation from the state of entropy'. A system at entropy is assigned an information measure of zero and a thermodynamic probability of one; and deviations from entropy are associated with decreasing thermodynamic probability and increasing information.

2.4 Summary

In 2.1 the information mode and the dynamical mode were distinguished as rate-independent and rate-dependent, respectively. We can also add that, under either the (quasi) linguistic or information-theoretic construals, the information mode is further distinguished from the dynamical mode in that it is closed to complexity. The dynamical mode is most obviously open to complexity at the terrestrial scale and how it can be so is the main issue of irreversible non-equilibrium thermodynamics (Section 3.0).

We remarked at the outset of Section 2.0 that the contemporary form of the complementarity argument is agreeable to us in part but not in total. There is agreement with the claim that information (for control) can only be an alternative description of the dynamics; there is disagreement with the claim that this alternative description is symbolic, language-like and arbitrary with reference to the dynamics with which it is associated. To pursue and to abide by a definition of information in which information is closed is to run counter to an understanding of order as an *a posteriori* fact, that is, to run counter to the understanding that a large aggregation of atomistic particulars evolve toward decreasing entropy.

There is a distinction owing to Tomović (1978) that parallels the artifactual–natural distinction drawn above and that similarly expresses the qualms registered here with the direction of the relation between the informational and dynamical modes. Tomović (1978) refers to the conventional view of the relation of the informational mode to the dynamical mode as a direct plant–model relation where the model is derived from the plant by a logical process (of abstraction). The benchmark of a system abiding by this relation is that the products of the system may equal but not exceed the control potential contained in the initial algorithms: computers cannot outperform the control rules that govern their operation. The unconventional view of the relation of the informational mode to the dynamical mode is referred to by Tomovic (1978) as an inverse plant–model relation where the model arises from the plant by a dynamical process. the benchmark of a system abiding by this relation is that the products of the system necessarily exceed its initial control potential.

We are inclined to read these various considerations as follows: (i) a construal of information should be sought such that 'information' can be self-complexing; (ii) for the most general of cases the conception of information cannot be arbitrarily related to dynamics; and, relatedly, (iii) the predicates of information, when properly construed, ought to be dynamical in some sense of that word.

3 THE NATURAL PERSPECTIVE: PHYSICAL THEORY AND SYSTEMIC BEHAVIOR AT THE SCALE OF ECOLOGY

The problem of co-ordinating and controlling the body's many degrees of freedom consonant with the Principle of Similitude resides at the ecological scale. It is, therefore, a description of physical theory and systemic behavior at the ecological scale that we seek. The present part of the paper is intended to provide a historical overview of physical perspectives. Our intent will be to highlight the traditional tendency to select as primary a particular scale of physical reality from which to forge an understanding of the nature of 'causal dynamics' at all scales, and to identify the various philosophical attitudes that were deduced from particular physical perspectives. What follows is an identification of the philosophical perspective that we take to be proper for the ecological scale, a perspective that suggests significant constraints on physical theory as it bears on naturally developing systems.

3.1 Classical Mechanics

Between the sixteenth and nineteenth centuries physical science made significant advances concerning the laws governing motions of bodies through space at the scale of celestial activity. In particular, Galileo and Newton formulated laws making it possible to determine with precision the past and future states of certain mechanical systems. These laws formed the basis of *classical mechanics*. That these laws might be applicable to scales other than that of celestial activity gave rise to a scientific ideal that received its most celebrated expression in the writings of Laplace in the eighteenth century; namely, that it was possible to regard the behavior of any physical system as determined ultimately and completely by the laws of classical mechanics. Laplace's only requirement was that full knowledge be available, at any instant of time, of the composite forces and positions of the system. Given the composite force configuration, all future and past events could be completely determined merely by applying the laws of mechanics. Laplace's argument was the classical foundation of the so-called mechanistic perspective on natural phenomena (cf. Bohm, 1957). The working hypothesis of mechanism stated that ultimately any set of phenomena could be reduced, completely and unconditionally, to nothing more than the effects of some definite and bounded set of *fixed* laws which *determined* completely and precisely the phenomena. The conclusion drawn from the hypothesis was that systemic behavior on any scale of analysis and under any set of conditions could be determined, requiring only the specification of a set of initial and boundary conditions.

According to the Laplacian philosophy of mechanism, each and every system behaves in a determinate manner indifferent to its complexity. The degree of systemic complexity was not a factor to be considered in applying the philosophy; more importantly, perhaps, the Laplacian mechanistic stance does not refer to any means by which complexity can be fashioned. Laplacian mechanism does not address issues of complexity; rather it addresses issues of state transitions where the successive states are equivalent in complexity. Laplacian mechanism does not provide any means by which the system can change its degree of order and, therefore, the development of new order is outside the purview of a mechanistic philosophy.

3.2 Statistical and Quantum Mechanics

During the prior and present century, the view of classical mechanics was profoundly altered by the increasingly apparent confirmation of atomic theory. Whereas representation of macro-physical qualities of classical mechanics was by a *continuous* function of space x and time t, $B(x, t)$, kinetic atomistic theory considered matter and energy as collections of a huge number of *discrete* particles moving under the influence of mutual forces and it represented the micro-physical qualities by functions on the phase-space co-ordinates $(q_1, \ldots, q_n, p_1 \ldots, p_n) = (q, p)$ and on the parameters x and t: $b(q, p; x, t)$. Moreover, whereas the behavior of systems on the macro scale of classical mechanics could be continuously and *determinately* specified, the behavior of systems on the micro scale of quantum mechanics had a fundamentaly discrete and *statistical* character associated with it. The nature of this statistical character is duly expressed first by mean free path, relaxation time relations in the 19th century and in the Heisenberg uncertainty relations in the 20th century. Even if the maximum possible information about the state of the system is available, only statistical predictions about the values of the observables are possible. According to these discrete formulations of the uncertainty relations, the function defining the phase space $(q_1, \ldots, q_n, p_1, \ldots p_n)$ could have only a statistical distribution associated with it, leading to a probabilistic description of the activity of individual particles.

A statistical description of a dynamical many-body system can be represented as a collection of points in phase space, each point being weighted by a certain number. The total collection of weighted points defines the probability distribution and is termed an *ensemble*. Put simply, an ensemble is a discrete set of atomistic particulars standing in a continuous interrelation, where the interrelation is described by a distribution function. The observed value of a dynamical function, both local and in a more extended sense, is identified with the ensemble average of the microscopic function.

It became apparent by the twentieth century that the laws of quantum mechanics provided a precise description of micro behavior at the atomic or molecular state, and that the laws of classical mechanics provided a sufficiently accurate description of behavior at the macroscopic scale. The strikingly different character of behavior at these two scales, however, underlined the need for an explanation of the laws of continuous macro-physics as a consequence of the microscopic evolution of motion of matter as ensembles of discrete particles. A bridge between the two scales was proposed in the form of statistical mechanics.

Statistical mechanics established a formal link between the microscopic dynamical functions $b(q, p; x, t)$ and the macroscopic dynamical functions $B(x, t)$. It postulated the existence of a unique mapping correspondence between the microscopic phase space and the macroscopic state space:

$$b(q, p; x, t) \rightarrow B(x, t)$$

According to the postulate at any point in time the 'state' of a system was determined by a distribution function $F(q, p)$ satisfying

$$\int dq\, dp\, F(q, p) = 1$$

The observable value $B(x, t)$ of a dynamical function $b(q, p; x, t)$ in a system was given by

$$B(x, t) \langle b \rangle = \int dq\, dp\, b\,(q, p; x, t) = F(q, p)$$

By adding the extra condition $F(q, p) \geqslant 0$, $F(q, p)$ could be interpreted as the probability density for finding the system at the point q, p in phase space. Since the probability is postulated to be positive, $F(q, p) \geqslant 0$, the system's state is guaranteed to be somewhere in the phase space. The concept of state of the system is such that at time t, every point in the phase space represents a possible configuration of the system where each point is weighted by a value $F(q, p)$ of the distribution function (see Balescu, 1975 for a more complete analysis of statistical mechanics).

Statistical mechanics however proves to be a less than ideal bridge between the two scales. The mapping function from the micro phase space into the macro state space, $b(q, p) \rightarrow B$, specifies the existence of a unique correspondence in the direction of the micro-physical to the macro-physical. The mapping states that 'to every $b(q, p)$ there corresponds one and only one B.' The reverse of this statement, however, is *not* true. The statement 'to every B there corresponds one and only one $b(q, p)$' is *false*. The reason for this is that not all macroscopic qualities can be expressed in the form of an average of a dynamical function weighted with a distribution function, F.

In short, there is a one to many mapping from micro to macro and a many to one from macro to micro. In physical theory it is common that the set of macroscopic qualities is subdivided into two classes: the *mechanical* qualities, of the above form, and the *thermal* qualities, of a different form. The thermal qualities are typical of thermodynamics and are not treated by single particle analysis. It is difficult to assign certain qualities – such as temperature – any microscopic meaning. They generally are conceived of only at the macroscopic scale. For example, one speaks of the energy (that is, a mechanical quality of motion) of a single molecule, but one does not speak of the temperature of a single molecule. With this limitation, one defines these thermal qualities (such as temperature, entropy, etc.) entirely in terms of properties of the ensemble distribution, rather than as averages of single-particle properties. These are examples of *collective* properties whose values are determined by the overall distribution of all the particles in the system. The importance of the relationship between the mechanical and thermal properties will be discussed in the next section (on thermodynamics). Before proceeding, however, let us consider the role played by quantum principles in motivating philosophic attitudes.

The assertion of the statistical nature of quantum mechanics rested on two assumptions: the first one originated in Heisenberg's Uncertainty Principle; the second, following from uncertainty, eliminated the possibility of any precise identification of the initial state of a many-body system. Extending those assumptions, Heisenberg postulated the existence of a formal relationship between quantum mechanics and philosophy. Using the strong form of the law of causality, viz., that 'the exact knowledge of the present allows the future to be calculated,' Heisenberg noted that 'it is not the conclusion that is false but the hypothesis that is false' (cited in Jammer, 1974, p. 75). The uncertainty principle, by ruling out determination of an exact initial condition, eliminates the possibility of exact prediction of future events. Heisenberg concluded that 'since all experiments obey the quantum law and, consequently the indeterminacy relations, the incorrectness of the law of causality is a definitely established consequence of quantum mechanics itself' (p. 75). In short, Heisenberg was promoting a philosophic attitude of *indeterminacy*. Not even a Laplacian superbeing (capable of measuring a system and obtaining information about it without disturbing it) could make precise predictions about a system's future.

A second philosophic attitude arose from the problem of measurement associated with Heisenberg's uncertainty principle: the position and momentum of a particle cannot be determined simultaneously with arbitrary precision. The smaller the error committed in the measurement of momentum, the larger the uncertainty of the position (and vice versa). Most outspoken on this issue was Bohr who in 1927 noted that:

> the definition of the state of a physical system, as ordinarily understood, claims the elimination of all external disturbances. But in that case, according to the quantum postulate, any observation will be impossible, and above all, the concept of space and time lose their immediate sense. On the other hand, if in order to make observation possible we permit certain interactions with suitable agencies of measurement, not belonging to the system, an unambiguous definition of the state of the system is naturally no longer possible, and there can be no question of causality in the ordinary sense of the word. The very nature of the quantum theory thus forces us to regard the space–time co-ordination and the claim of causality, the union of which characterizes the classical theories, as complementary but exclusive features of the description, symbolizing the idealization of observation and definition respectively (cited in Jammer, 1974, p. 87).

According to Bohr, 'space–time co-ordination' and 'causality' are related in a complementary manner on the quantum scale, an interpretation which has come to be known as the 'complementarity interpretation' or 'Copenhagen interpretation' of quantum mechanics (cf. Jammer, 1974, for an excellent account of the entire history of quantum mechanics). We outlined a contemporary version of the Copenhagen interpretation and its bearing on the character of complex systems in 2.1 above.

3.3 Classical Equilibrium Reversible Thermodynamics

Within the past hundred years it has become increasingly apparent that at a scale greater than that of the quantum scale and less than that of the celestial scale, certain conditions reveal a dramatically different view of 'causal dynamics.' It is at this scale that variations in thermal flows such as entropy become sufficiently prominent so as to compete with the classically defined mechanical forces such as gravitational (where mass is above a critical level) and electrostatic (where mass is below a critical level). The result of these competing 'flows' and 'forces' is the possibility that the state of the system can systematically 'increase' its order. Thus, the second law of thermodynamics, viz. the principle of increasing entropy, which is prescriptive of *disorder* at the celestial and quantum scale can nevertheless be prescriptive of *order* when certain conditions on the law, such as those found terrestrially, prevail. An understanding of this significant fact rests on an analysis of the conditions that raise and lower thermal flows. The beginning of such an analysis is provided by thermodynamics.

Thermodynamics deals with the transactions of various forms of energy in all of its possible forms. Thermodynamics does so by describing a system in terms of concepts and laws derived from the study of macroscopic phenomena such as pressure, volume, temperature, concentrations, etc. The boundary of such a system is a mathematical surface which separates an exterior or surrounding system from an interior system. Using these guidelines any physical or chemical system can be described as a thermodynamic system.

Thermodynamic system properties are subdivided according to the exchanges of energy (heat and work) and matter through their boundaries. A system can be classified as an *isolated* system when it exchanges neither energy nor matter with its surroundings. An example of an isolated system is a coffee thermos; once the coffee is poured into the thermos and the thermos is sealed no further heat is added. Strictly speaking, however, it is not a real isolated system because it eventually loses (exchanges) heat to its environment (see Figure 1). A second system is classified as *closed* when it exchanges energy but

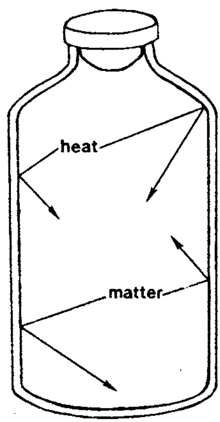

FIGURE 1 *Isolated system:* heat and matter cannot leave or enter the system

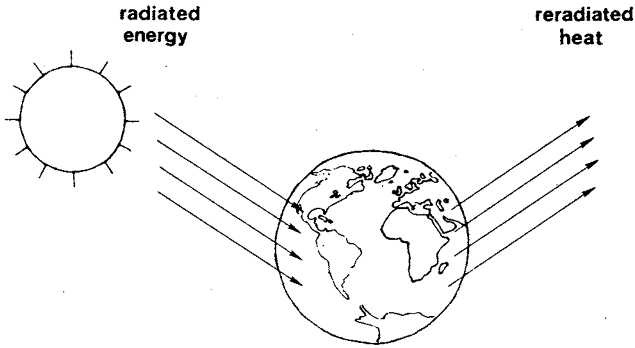

FIGURE 2 *Closed system:* matter cannot cross the boundary but energy can be exchanged across the boundary

not matter with its surroundings. The earth may be viewed as an example of a closed system insofar as it does not receive nor expel significant amounts of matter (the amounts lost into space or gained through meteorite fall, etc. are negligible). It does exchange energy, as heat is both received from and reradiated into outer space (see Figure 2).

Finally, a third system is classified as *open* when it exchanges *both* energy and matter with its surroundings. A biological cell is an example of an open system. Both energy and matter can be exchanged with the cell's surroundings through the cell membrane. The cell's membrane is differentially permeable allowing only certain substances to enter and leave the system (see Figure 3).

Classical thermodynamics originated from a few empirical observations on the behavior of (in principle) isolated systems. These observations were organized and axiomatized in the form of 'three laws.' For our present concerns we need consider only the first two of the three laws. The first law is the

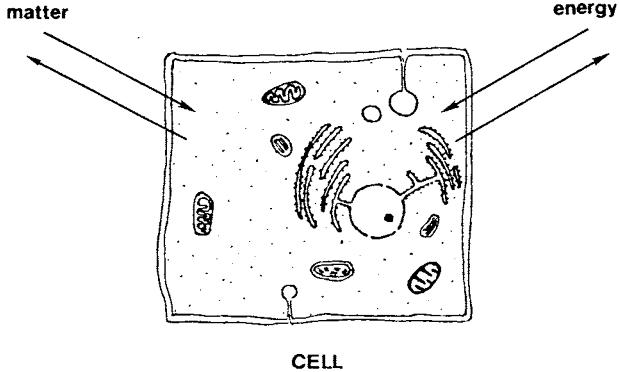

FIGURE 3 *Open system:* both matter and energy pass through the boundaries

law of conservation of energy: in all macroscopic chemical and physical processes, energy is neither created nor destroyed but merely transformed from one form to another. For example, while energy may be transformed (as in the case of a chemical form to a mechanical form in an internal combustion engine) there must exist a *conservative* quantitative correspondence between the different kinds of energy.

The second law of thermodynamics (in one of many equivalent forms) states that: any spontaneous process results in an increase in the disorder of the system plus its surroundings. This law provides a criterion for predicting the temporal *direction* of a given process. First, it recognizes a measure of state or condition of matter and energy called entropy, which can be defined or identified with randomness or disorder. Second, it states that all physical and chemical processes proceed in a direction such that the randomness or entropy of the universe – the system plus its surroundings – increases to a maximum possible; when the local ensemble can no longer undergo any such change, then at this point there is local *equilibrium*. According to the second law no process can occur which results in a decrease in the entropy of the universe. The law predicts destruction of local regions of inhomogeneity of molecular configurations and a tendency to establish uniformity. In short, systems tend to approach equilibrium states in which temperature, pressure, and other measurable parameters of state become locally uniform throughout. Once at equilibrium there is no tendency to spontaneously change back to nonuniform or nonrandom states.

Theoretically the entropy of a system may also remain *constant* during a process, and when it does such a process is defined as being *reversible*. In a reversible process the path described by the process passes through an infinite succession of intermediate states all of which are at equilibrium. While reversible processes are theoretically possible, completely reversible processes in which entropy remains constant are rare physical occurrences. In order for such ideal processes to occur, time would have to approach infinity to provide the necessary slow rate of change. Because of this, time as a variable does not enter into the formalism of the two classical laws. The laws deal strictly with energy changes as a system assumes new equilibrium states. Due to the time independent nature of these laws it has been argued that they should be termed laws of 'thermostatics' rather than thermodynamics (Bridgman, 1941; DeGroot and Mazur, 1962; Iberall, 1978).

3.4 Nonequilibrium Irreversible Thermodynamics: The Linear Range

Let us now extend our discussion of thermodynamics beyond the reversible equilibrium states associated with locally isolated systems, and into the non-equilibrium irreversible states associated with open and closed systems. In the previous section we noted that the second law of thermodynamics postulates the existence of a state function – the entropy function – and the tendency of the function to increase monotonically until it reaches its maximum at thermodynamic equilibrium. Using the concept of change in entropy, dS, during a time dt we can distinguish between two types of processes: reversible and irreversible. Reversible processes are defined as those processes in which entropy changes are zero. In contrast, irreversible processes are defined as those processes in which entropy changes are always greater than zero. More specifically, irreversible processes are defined on the basis of the properties of the state function, S, in terms of the rate of dissipation per unit time, the so-called *entropy production*.

Consider a system *open* to the exchange of energy and matter with its surroundings. The entropy change during a time interval dt may be decomposed as follows (Prigogine, 1947, 1967; Glansdorff and Prigogine, 1971):

$$dS = d_e S + d_i S$$

with

$$d_i S \geqslant 0$$

where $d_e S$ is the flow of entropy due to exchange with the surroundings and $d_i S$ is the entropy production inside the system due to irreversible processes (see Figure 4). According to the second law of thermodynamics $d_i S$ must equal zero for reversible (or equilibrium) processes and be positive for irreversible (or nonequilibrium) processes. For an isolated system, where the flow of entropy between systems is ruled out, the state entropy function reduces to:

$$dS = d_i S \geqslant 0 \quad \text{(isolated system)}$$

The inequality indicates that the entropy production for an isolated system will tend irreversibly to an equilibrium state where $d_i S = d_e S = 0$. The behavior of an isolated system is, therefore, always defined with reference to the second law of thermodynamics, namely, the state entropy function.

Consider, for example, a gas in an initial state where a certain degree of order has been imposed, such as confining it to one half of a container by a partition. And consider further that the system is isolated from the exchange of matter or energy with its surrounds. If the partition is now removed, the gas will rapidly tend to occupy the entire volume and reduce the initial order as

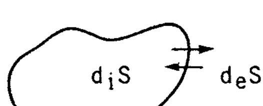

FIGURE 4 Entropy flow ($d_e S$) entropy and entropy production ($d_i S$) in an open system

defined by the second law. In this regard the process irreversibly tends to a state of equilibrium whereby once at equilibrium the inverse process cannot spontaneously occur. Thus once equilibrium is achieved time-dependent reversible processes begin which are stable with respect to disturbances. The behavior of an isolated system may be characterized by a tendency for the state entropy function to increase monotonically until it reaches a maximum at thermodynamic equilibrium. *The spontaneous formation of ordered structures is therefore ruled out for isolated systems.*

Consider next a closed system that is at equilibrium but which can exchange energy (but not matter) with its surroundings. Let the surroundings be at a certain constant temperature. This situation is similar to the isolated condition except that the state function S is not the sole determinant of the resulting behavior, there is an additional state function to be considered, the Helmholtz free energy, F, defined by:

$$F = E - TS \quad \text{(closed system)}$$

where E is the energy of the system and T is the absolute temperature (in degrees Kelvin). Whatever configuration an isolated system assumes results from a competition between energy and entropy. At a sufficiently low temperature, energy becomes the dominant factor in the competition with entropy and the isolated system assumes a configuration favoring a minimum of potential energy. In this case the entropy contribution is small compared to that of free energy. At increasing temperatures, however, an isolated system graduates to structures of increasingly higher entropy. Since Boltzmann first identified the shifting outcome of the competition between energy and entropy as a function of temperature in the Boltzmann factor, $\exp(-E/kT)$, an increase in entropy with increasing temperature is termed the *Boltzmann ordering principle* (cf. Nicolis and Prigogine, 1977). The competition at the microscopic scale appears macroscopically in the form of phase transitions, ferromagnetism, etc. The Boltzmann ordering principle prescribes that below a certain critical value of the temperature gradient, microscopic fluctuations due to entropic tendencies are damped and disappear. Thus in equilibrium phase transitions, order arises from the elimination of fluctuation. For example, the gradual elimination of molecular agitation defines the transition from gas (least ordered) to liquid, to ice (most ordered) in the phase changes of water. In sum, Boltzmann's principle provides a primitive means for understanding how order might originate. However, the principle's excessive dependency on (decreased) temperature for the origin of structure strictly curtails its generalizability to biological order.

Classical thermodynamics deals with the equilibrium conditions described above in which the entropy production term goes to zero. We now turn to an analysis of nonequilibrium conditions in which the entropy production term becomes a critical factor. Before extending our analysis to nonequilibrium conditions however, one assumption must be made concerning macroscopic properties such as entropy and thermal flows. It is assumed that the macroscopic properties can be described in terms of a limited number of *local* variables and that these variables continue to relate in the manner that they relate in equilibrium conditions. The validity of the *local equilibrium* description has been investigated extensively starting most notably with Maxwell's kinetic theory of gases. The theory of local equilibrium was advanced historically by way of initial arguments by Boltzmann, with sharp tests provided by Helmholtz and Kirchoff, with codification of the reversible state provided by Gibbs, and the nature of the approach toward equilibrium provided by Boltzmann's H theorem (Chapman and Cowling, 1952; Tolman, 1938). The modern clarification of the *physics* of the linear law operating at local equilibrium was set forth by Onsager (1931). More recently its application has been opened for further discussion, in the theoretical case, by Prigogine and his colleagues (Prigogine, 1947; Nicolis and Prigogine, 1977) and been shown to hold true for conditions near equilibrium. In essence, the validity of the local equilibrium assumption implies that collisional effects are sufficient to *damp* deviations from a steady nonequilibrium state condition (that is to treat the approach toward equilibrium as a linear transport conductance).

Deviations from equilibrium that assume a degree of stability, so-called steady states, are maintained by virtue of *entropy production.* As noted earlier, the total entropy production dS can be decomposed into an entropy flow (d_eS) exchanged with the environment and an entropy production (d_iS) due to the irreversible processes. The explicit evaluation of the entropy production is described by the following balance equation:

$$P[s] = \frac{d_i S}{dt} = \int dV J_p X_p = \int dV \geqslant 0 \qquad (1)$$

where the sign of d_iS is derived from the second law of thermodynamics. The J_ps and X_ps are, respectively, the conjugate thermodynamic flows and forces of the irreversible processes. It is necessary to understand how the *kinematic* rates of flow (J_p), which are in principle unknown quantities, are related to the *dynamic* forces (X_p), which are known functions of the composite variables. We begin with the equilibrium condition.

At equilibrium both the flows (J_ps) and forces (X_ps) vanish

$$\begin{matrix} J_p = 0 \\ X_p = 0 \end{matrix} \quad \text{(at equilibrium)}$$

and entropy production goes to zero

$P[s] = 0$ (reversible process connecting two equilibrium states)

$P[s] \geqslant 0$ (irreversible process producing entropy)

For conditions near equilibrium the J_ps behave as a *linear* function of the X_ps and equation (1) becomes quadratic (Glansdorff and Prigogine, 1971). This argument is based generally on Onsager's reciprocal relationships (1931). In this regard Prigogne (1947, 1967) has shown that when processes do not deviate far from equilibrium and when boundary conditions remain time-independent, *a steady-state condition is specified by the minimum of the entropy production function*. This is known as the *theorem of minimum entropy production*. Under these *nonequilibrium* conditions the entropy production function acts in the same fashion as the state functions of entropy and free energy in the equilibrium conditions. Therefore, when a steady state occurs in near equilibrium conditions the system behaves with reference to the state entropy production function where the steady state is characterized by an extremum principle defining the minimum of the function (Prigogine, 1947; Glansdorff and Prigogine, 1971). Care should be taken not to confuse the steady nonequilibrium state with the equilibrium state that is characterized by a zero entropy production condition.

In terms of stability, the steady nonequilibrium state condition exhibits the same stable properties associated with the equilibrium condition with regard to disturbances. All local perturbations or fluctuations that deviate from the steady state are asymptotically damped back to the steady state by the entropic tendency of irreversible processes. *Because of the asymptotic behavior around a single steady state the development of new and more complex order such as that manifest in biological development must be ruled out within the linear domain of the equilibrium condition.*

Before discussing a nonlinear domain which might potentially exist in far from equilibrium conditions, we summarize systemic behavior in the linear domain: all systems operating at near equilibrium conditions, independent of how complicated the reaction mechanisms are, respond to small deviations from an equilibrium or steady state with a fading or damping behavior which is *linearly* proportional to the magnitude of the deviation.

3.5 Nonequilibrium Irreversible Thermodynamics: The Nonlinear Range

A distinction must be made which is commonly passed over. There is a difference in the formal treatment of the mathematical nonlinearities at the macroscopic scale and the mathematical nonlinearities at the scale of local atomistic interactions. Whereas the macroscopic nonlinearities are recognized explicitly in the physical equations, the microscopic nonlinearities cannot be; rather they are captured, in the thermodynamic approximation, by macroscopic *linear* laws. Under the conditions of mathematical nonlinearities the possibility exists for the realization of a threshold beyond which the previous steady state becomes unstable in a mathematical sense and can be replaced by a new class of mathematical regimes having completely different spatial and temporal orderings. Such transformations have been studied in both hydrodynamics and in phase transitions. More recently, Prigogine, motivated by problems in chemically reactive fields, has also made contributions toward understanding these orderings. Prigogine has labeled the orderings *dissipative structures*. In what follows we will briefly describe an extension of thermodynamics to nonlinear ranges that has been advanced by Glansdorff and Prigogine (1971). The approach entails an extension of the theorem of minimum entropy production.

For thermodynamic processes within the linear range, variations in entropy production dP/dt are always less than or equal to zero: $dP/dt \leqslant 0$. The equality refers to a steady-state situation and the inequality refers to irreversible processes tending towards a steady state. When the steady state occurs near equilibrium, the behavior is characterized according to the extremum principle of minimum entropy production. For states far away from equilibrium, the inequality dP/dt may break down such that no extended inequality can be found that would guarantee the stability of a steady state. In fact Glansdorff and Prigogine (1971) have shown that beyond the linear range, dP/dt does not exhibit any inequality which would guarantee the stability of a steady state. While no singular point of stability could be found in the entropy production function, Glansdorff and Prigogine (1971) derived an alternative state function which revealed potential stability points. The new state function was termed *excess entropy production* and was expressed by the following equation:

$$1/2\delta^2 P = \int dV\, \delta J_p\, \delta X_p \geqslant 0 \tag{2}$$

Here J_p, X_p are the *excess* flows and forces resulting from deviations of the system from a stable state. Deviation can result from either random or systematic disturbances acting on the system. For states close to equilibrium $1/2\delta^2 P$ behaves as a quadratic function exhibiting a positive value specifying a stable state. However, for states far from equilibrium this need not be the case. Instead, the excess entropy production can approach zero, creating a marginal state of stability in which a 'sudden' transition occurs moving the system from a previously stable state to an instability. The instability results in the system's *amplification* of its fluctuations which drive the system to a new spatiotemporal ordering. In contrast to equilibrium and steady-state conditions, where fluctuations are asymptotically damped, the above instability results in an amplification of the fluctuations which ultimately reach a macroscopic level and finally stabilize to a new regime. These symmetry-breaking instabilities are of interest since they reveal a means by which the system spontaneously self-organizes in a stable fashion.

It is important to note that the excess entropy production inequality applies not only to the nonlinear range, but also to the linear range, where it becomes equivalent to the theorem of minimum entropy production. Because of the generality, the inequality has been called a *universal evolution criterion* (cf. Glansdorff and Prigogine, 1971). In short, the above inequality provides a thermodynamic criterion for all nonequilibrium states. In regions near equilibrium, the inequality is always satisfied with a positive value. For regions far from equilibrium, the inequality may approach zero, creating an instability, and may ultimately move the system to a new spatiotemporal ordering. In other words, as a system is driven further away from equilibrium, a single solution can 'branch' into several possible solutions, and each of these, in turn, may branch still further from equilibrium. The branches are referred to as *thermodynamic branches* and are similar to the 'bifurcations' or 'catastrophes' described by Thom (1975; and Section 4 below; see also Nicolis and Auchmuty, 1974, for a discussion of how the two concepts differ).

A variety of dynamic regimes may result from the thermodynamic branching surrounding the conditions of a dissipative structure: (i) the systemic behavior may consist of sustained multiple steady states with systematic transitions from one to another; (ii) the systemic behavior may be a rotation on a 'limit' cycle around an unstable singular point, resulting in stable oscillation (several limit cycles are possible); or (iii) the systemic behavior may be a sustained oscillation resulting in waves. Several examples will suffice to demonstrate the manifestation of these instabilities in nature.

The Bénard or convection instability is realized in a situation in which a fluid layer is heated from below and kept at a fixed temperature above so as to create a temperature gradient in opposition to the effects of gravitational force. At small values (within the linear range) 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 (passes into the nonlinear range) a convective, macroscopic motion occurs generally in the form of rolls or hexagons (for variations see Koschmeider, 1975, 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 (within the linear range) the fluid flow is laminar; above that value (in the nonlinear range) 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 endfaces of which mirrors are positioned. At small energy fluxes (within the linear range) the laser operates as a lamp – the atoms emit light wavetracks independently of each other. When the energy flux exceeds a critical value (passes into the nonlinear range), all the atoms oscillate in phase emitting a single and very large wave track of light.

In these examples we see that by scaling-up parameters into nonlinear ranges macroscopic structure develops from a homogeneous state of affairs or from a state of affairs of lesser structure. The new stability that develops beyond a critical scale value may in turn give way to a further, different stability at higher scale values. At supercritical values (in both the Bénard and Taylor situations), periodic pulsing characterizes the newer stabilities that replace those that appear at the critical value. The critical scale value may be expressed in terms of dimensionless parameters, such as the Reynolds or Rayleigh numbers.

Let us consider a less familiar philosophic attitude that might be associated with the nonequilibrium-state situations referred to above. We noted that the behavior of dissipative structures is characterized by a tendency not to run down but rather to establish temporary steady-state regimes displaced from global equilibrium. Maintenance of the regimes is through a continual flow of free energy and matter into and out of the operational components of the system (cf. Iberall, 1977, 1978; Morowitz, 1978; Prigogine *et al.*, 1975). Of particular importance is the fact that these systems exhibit: (i) the ability to self-organize and (ii) the phenomenon of autonomy as exhibited by their ability to resist the traditionally dominant effects of initial and boundary conditions. Consider first the phenomenon of self-organization.

Self-organization occurs only under certain *open* conditions, where the amplification of fluctuation leads to an instability resulting in the emergence of a new thermodynamic branch. Symmetry is broken and new structures are formed out of the resulting instability. The new structures may possess new functions that correspond to a higher level of symmetry (interaction) between the system and its environment. The critical event in the symmetry-breaking instability is the realization of a scale change defined over the bifurcation parameters. The scale change is expressible in terms of a dimensionless number (see 1.2 above) such as the generalized Reynolds or Rayleigh numbers. During the scaling-up process there is no explicit *a priori* specification or representation of the new structure, which would remove such a phenomenon from the class of self-organizing systems. Indeed, the new structures arise as an *a posteriori* fact of the system through the act of drawing on a source of high free energy, passing it through the operational component parts of the system and finally dissipating the resulting heat into an external sink. Through amplification of the previously damped nonlinearities on the micro scale, new stabilities may result on the macro scale. Thus dissipative structures are said to exhibit the property of self-organizing or self-complexing: the systemic ability to develop a greater degree of order from a state of affairs of a lesser degree of order.

With respect to the phenomenon of autonomy, we will consider two related properties associated with it. First, dissipative structures exhibit a relative immunity to disturbances in initial and boundary conditions. Small deviations or perturbations in either of these conditions do not change the stable behavioral patterns of these structures. Indeed, the stability of dissipative systems is guaranteed by dimensions *intrinsic* to the system. More commonly this is known as *equifinality*. No longer are the system's dynamics causally linked in a determinate fashion to the system's environment. The system now exhibits a degree of autonomy earmarked by its stability with respect to perturbations.

The second characteristic of autonomy concerns the selection of *particular* stable modes at the bifurcation points. At these points the symmetry-breaking instabilities may reveal multiple stable modes. While the thermodynamic branches are themselves determinately specific, at least in principle, by stability and bifurcation theory, the actual specification of which branch the system enters may ultimately be *nondeterminately* specified by a dimension intrinsic to the system. Only when a system is scaled-up beyond some critical dimension are the nonlinearities sufficiently amplified to lead to these choice points between various solutions (Hanson, 1974). At this point the system achieves additional autonomy with respect to the outside environment. Prior to the scaled-up condition (i.e. within the linear region) the system behaves in a determinate fashion; after the critical condition is reached, the system exhibits stability. In sufficiently complex systems where the thermodynamic branches are multiple, such as those manifest in biological systems, local intrinsic dimensions may specify the particular behavioral mode. This autonomy is ultimately manifest in the macro-structure of the system's behavior.

Nondeterminacy stands in sharp contrast to determinacy, a notion associated with the dynamics of Laplace's celestially scaled system, and to indeterminacy, a notion associated with the dynamics of Heisenberg's quantum system. In contrast to the macro and micro scales associated with determinacy and indeterminacy respectively, nondeterminacy is a phenomenon associated with the dynamics of terrestial activity, activity at the scale of ecology. At this medium-range scale, the micro and macro flows and forces enter into a competing relationship allowing for the possibility of systemic order arising under certain conditions. Only at this scale is there sufficient flexibility and stability to allow for their working relationship to be realized where entropy becomes an active contributor towards order.

If we were to follow the earlier tradition of Laplace and Heisenberg we might now be tempted to postulate that the nondeterminacy revealed in the system's dynamics might be generalized to all scales and to all domains. However, we have seen, in the above analysis of nonequilibrium thermodynamics, that scale factors play a critical role in determining the nature of the causal dynamics associated with any systemic activity. At one scale a system may behave in a causally determinant manner, while at a slightly increased scale the system's behavior may dramatically change such that the previously dominant effects of initial and boundary conditions are now resisted by properties intrinsic to the system.

The upshot of the foregoing for the general conduct of science should be highlighted. The argument given amounts to a strong rejection of the traditional form of reductionism. The advocated strategy for the unity of science was to identify one scale as fundamental and then to identify bridging statements between the (special) predicates of the 'unreduced' scale and the (fundamental) predicates of the 'reducing' scale. This matching of predicates was intended to bring the phenomena at the unreduced scale under the laws governing phenomena at the reducing scale. The assertion that the traditional form of reductionism can succeed even in principle is responded to with well-grounded skepticism (e.g. Bunge, 1977; Fodor, 1975). What the arguments given amount to on the positive side of the ledger is an advocacy of a new strategy for the unity of science – a reductionism (if that word has legitimacy in the new formulation) not to *physical things at some privileged scale* but to *physical principles (or strategies) that are independent of scale*. Iberall (1977), Yates (in press) and Soodak (Soodak and Iberall, 1978) have publicized their pursuit of common principles that can be applied repetitively and with equanimity across scales (and *a fortiori* across disciplines) to embrace the systemic phenomena that characterize them. It is to the version of thermodynamic theory advocated by these theorists – a version termed homeokinetics – that we now turn. Homeokinetic theory is like Dissipative Structure theory in that its principal focus has been the relation of thermodynamics to many complex systems, including living systems. Nevertheless the two theories do distinguish in nontrivial ways and these distinctions are noted.

3.6 Homeokinetic Physics

Homeokinetic physics was originally developed by Iberall (Iberall and McCulloch, 1970; Iberall and Soodak, 1978; Soodak and Iberall, 1978; Yates, Marsh, and Iberall, 1972) to provide an integrated account of the dynamics exhibited by biological organisms as a specific form of dynamic regulation (i.e. as an extension of the more static notion of homeostasis). But the notion of homeokinetics proves to be very general and applicable at all scales. *Homeokinetics* is meant to contrast with *homeostasis* (Cannon, 1939; Bernard, 1949). Homeostasis does not explicitly identify the mechanism of biological regulation. What is identified is some quasistatic regulation wherein basic properties and ongoing processes are preserved 'independent of external vicissitudes'. Homeokinetics views the mechanism of biological regulation and of regularity in general as a dynamic process of ongoing engine processes, 'oscillators,' whereby conserved regulated values arise as the consequence of a large spectrum of such autonomous oscillators. A conserved value is an averaged or mean state that emerges as a distributed property defined over the operating parameters of the system. Homeokinetics proposes that the autonomous oscillators are organized in accordance with the design principles of thermodynamic engines that draw on energy from a potential source, reject some to a lower potential sink and have capability to do work in a periodic, limit-cycle fashion (Iberall, 1977). The possible existence of such engine oscillators and their cyclic nature is defined in a theorem by Morowitz (1968, 1978): 'In steady-state systems, the flow of energy through the system from a source to a sink will lead to at least one cycle in the system.' The quality of the cycle is limit-cycle: the source–sink system oscillates between well-defined minimum and maximum values and it does so by virtue of being thermodynamically-open, nonconservative, dissipative and nonlinear.

As anticipated above, in its current and more general form (Iberall and Soodak, 1978; Soodak and Iberall, 1978; Yates, in press), homeokinetic physics argues for a single set of physical principles which are 'scale-independent' (e.g. from the largest to the smallest systems in nature), where scale is meant to define a relative order of magnitude. The principles strategically derive their substance from the domains of statistical mechanics, nonlinear mechanics, irreversible thermodynamics or pure physics in general. While the principles are equally valid for *all* physical systems, it is open systems at the terrestrial scale that we seek as test fields for homeokinetic theory.

3.6.1 *On the Arbitrariness of the Structure/Function Relationship in Open Thermodynamic Systems*

While accepting the observable reality of 'structure,' homeokinetic theory seeks out the dynamical functional basis for both structure and function. Central to the analysis is the identification of the operative thermodynamic engines. These engines are open systems, composed of active, interacting components of very many degrees of freedom. The material composition may vary dramatically from one engine to another, but the set of dynamic events which mark the system as a thermodynamic engine is unvarying. What earmarks thermodynamic engines is the invariant fashion in which these systems do their repetitive 'business' within the source–sink system of available energies. For example, structural properties of a plant, tree, organism or society will differ extensively but not intensively; qualitative dynamic properties (like the cycle) will remain invariant over all of these forms of thermodynamic engines.

In thermodynamic systems 'structure' and 'function' share a common format for their source of order. They differ only in the scale of their relaxation times and their energy levels. Quite generally, structure in the system is associated with a relatively slow relaxation time in comparison to function. In either situation, structure or function, order arises by virtue of cyclical transactions of energy through the source–sink system. In short, functions are not logically distinct from structures but rather partake of the same or related dynamic origins. Significantly, when structural properties are given a dynamic analysis their nonarbitrary relationship to functional properties should ultimately become apparent.

In this regard consider the often cited many-to-one mapping of structure to function. Because many different structural arrangements can be observed supporting the same dynamic event it is generally concluded that the relationship between the material support and its coordinate function is arbitrary. From the homeokinetic view this arbitrariness would be the mistaken consequence of a superficial analysis of the nature of the material composition.

3.6.2 The Homeokinetic Methodology: Biospectroscopy

Since the basic element of temporal organization is the cycle, one method of analysis characteristically advocated by homeokinetics is spectroscopy. Spectroscopy is a standard approach to periodic behavior where, for example, time series analysis is used to identify cyclic processes as a precursor to identifying repetitive, possibly invariant and essential, functions of the underlying mechanisms. Broadly speaking, spectroscopic analysis indexes the relationship between the important repetitive business going on within a system, and the process time domains in which it occurs (Iberall, Soodak, and Hassler, 1978).

The physical framework offered by Homeokinetic Theory (Iberall, 1972) for all of nature is an organization of operational components into successive levels of atomisms (A) and continua (c). The use of the term atomism denotes both the unit and the doctrine. It is used in a sense similar to organism. An ensemble of atomisms forms a continuum. The continuum then forms the basis for a new atomism at a larger scale, etc. The . . . A–c–A . . . series may become singular at either end. Each ensemble continuum of atomisms constitutes a collective system of thermodynamic engines with unique distribution functions associated with them. Under the appropriate open conditions thermodynamic engines emerge, where cyclicity will be manifest in accordance with the system's total thermodynamic bookkeeping activities.

At any organizational scale an ensemble of interacting atomistic entities acts in a thermodynamically near-continuous manner, bounded by an appropriate space–time scale (from above and below). While the ensemble may be *far from equilibrium globally, locally the system is thermodynamically near-continuous and in near equilibrium.* Under scale changes this fluid-like continuum may become dynamically unstable locally, whereby a spectrum of patterned functions, or in fact, precipitated structures, of superatomisms may emerge. While a field thermodynamic formulation is appropriate for a continuum condition, it is not appropriate for a discrete atomistic unit. At the atomistic level, more standard kinetic formulations are necessary. Homeokinetics in particular argues that mechanics implies thermodynamics as atomisms transform into continuum (Iberall and Soodak, 1978).

The range of rhythmic cycles exhibited by a system may vary greatly from slow to fast, where each frequency serves as a signature of various autonomous ensembles. From the ensemble perspective the unit of an individual oscillator appears within the thermodynamically complete and relatively autonomous system. However, from the perspective of the individual atomistic units the organization appears 'neighborly,' perhaps even chaotic and random. To capture the dynamics of the large ensemble requires minimally that: (i) the scale of observation be large compared to the mean free path of the atomistic units and (ii) the time of observation be long compared to the relaxation times of the interactions of the atomistic units (Yates, Marsh, and Iberall, 1972; Yates and Iberall, 1973). For example, an organism will exhibit a wide set of signal frequencies which correspond to various organs and tissue systems in the body (for examples see, Iberall and McCulloch, 1970; Iberall, 1969). This range may vary from the order of seconds to years depending on the organ. A set of faster frequencies can also be detected which form the atomistic basis for organs. The range of these frequencies may be on the order of milli- and microseconds. An upper limit may be found in the ecosystem where a single 'relaxation' process is revealed over the entire lifetime spectrum of the individual organism. The general strategy is to select the low frequencies first since they signify the near-static, steady states of the dynamic system. If these are not carefully defined and understood, then the faster frequencies will be less well identifiable (Yates, in press).

Below we present a brief summary of the steps involved in a homeokinetic analysis. We follow closely the steps presented by Yates (in press; see also Iberall and Soodak, 1978; Soodak and Iberall, 1978; Iberall, 1977; Iberall, Soodak, and Hassler, 1978; Iberall, 1978b, for the complete methodology):

1. Identify the atomisms. Any physical system has atomistic elements that must be identified. These may be extremely simple (i.e. have no internal degrees of freedom), or they may be complex, active elements with many internal degrees of freedom that equipartition energy slowly among these internal degrees of freedom. Examples of the atomism in the neuromuscular system are: muscle fibers, motor units, muscles, co-ordinative structures, and organismic activity (see Bloch and Iberall, 1974). It is important to note that each atomism is an 'ecosystem' on its own scale – it includes a source (of potential energy), a sink and a set of operational components. Moreover, each atomism has its own spectral properties. Significantly, the functional integrity of an atomism – its cyclicity – cannot be attributed to a part; it can only be attributed to the 'ecosystem' as a unit (cf. Turvey, Shaw, and Mace, 1978).
2. Identify the interactions between the atomisms. (Without interaction there is no system. The atomisms exchange energy and are bound together and kept from dissolving into each other by the few physical forces, e.g. electromagnetic and gravitational forces.)
3. Define the ensemble of like-interacting, active atomisms, including the space–time domains in which a continuum view is justified.
4. Define the complexions – the dynamic states in phase space. This constitutes a basis for computing a metric of complexity of the system.
5. Specify the thermostatic description (partitioning of energy, distribution function, thermodynamic potentials, constitutive relations of the equations of state, summational invariants).
6. Specify the field equations of change, in terms of change in average local values of summational invariants. (This is the irreversible thermodynamic account of response to external influence from region to region. This thermodynamic description holds in the response range in which transport coefficients in the equations of change are functions of thermodynamic variables only, but not of time; i.e. are describable by autonomous differential equations. Nonequilibrium, irreversible thermodynamics is limited to conditions that are locally near equilibrium, see below.)
7. Identify the field boundary conditions.
8. Identify the thermodynamic engine processes that are manifest as cyclic processes (limit cycle behavior) at each level.
9. Specify the field mechanics for the whole system, arising out of its various equations of change.
10. Identify the history of the system. This is the trajectory resulting from slow changes in the system parameters. This step is meant to

acknowledge the nonautonomous aspects that arise from outside interactions.

3.7 Dissipative Structure Theory and Homeokinetic Theory: Compared and Contrasted

Dissipative Structure theory and Homeokinetics both address questions relative to the design logic for spatiotemporal order in natural systems. Indifferent to the fact that the system is termed a 'dissipative structure' or a 'thermodynamic engine' the following requirements must be satisfied:

1. A source of potential energy from which (generalized) work can arise.
2. A microcosm of operational components with a stochastic fluctuating nature.
3. The presence of nonlinear components.
4. A scale change such that a nonlinear response is critically amplified (in the sense that the system's own dimensions now resist previously dominant initial and boundary conditions).

If these conditions are met, then the possibility exists for the transition from a stochastic steady-state situation to a spatially or temporally structured, steady-state situation (or a time-dependent limit-cycle regime) characterized by homogeneous oscillations or by propagating waves.

According to dissipative structure theory, spatiotemporal orderings are realizable only in the entire field for far from equilibrium conditions. While both theories agree that the 'start-up' phase involving the sudden transition from one ordered state to another requires a far from equilibrium condition, in the entire field, they differ in how they stress their equilibrium requirement. Dissipative Structure theory states that new stability regimes are both 'started-up' and 'maintained' in far from equilibrium conditions. In contrast Homeokinetic theory argues that the local fields before and after start-up are near equilibrium, and thus in the domain of irreversible thermodynamics. After an initial start-up phase, involving some shock waves, a system moves back toward a near-equilibrium state where thermostatic conditions can prevail *locally*. Globally, however, the system is still in a far from equilibrium condition. By maintaining local near equilibrium conditions, a mature biological system does not have to continually transform large energies at high rates as would be required if far from equilibrium conditions also prevailed locally (cf. Morowitz, 1978). Once the spatiotemporal structures are established, maintenance of the structures may be achieved through continuous near-equilibrium transport processes (for more on the transport problem see Iberall, 1977).

A second contrast involves the metholdogy employed by the two theories. For Dissipative Structure theory the methodology entails formulation of a set of nonlinear kinetic equations that correspond to, and form the explanation of, the sudden transition in ordered states. Originally the methodology was applied to test fields involving chemical reactions occurring in series and parallel. Recently the methodology has been extended to ecological and social fields. In these situations sudden transitions in the field reactions are modelled by *kinetic formulation* of 'flow fields,' which are not regarded to be a *thermodynamic formulation* (for examples see Prigogine, Allen, and Herman, 1977). From the perspective of Dissipative Structure theory, kinetic formulations and thermodynamic formulations relate in a *complementary* fashion (Prigogine, 1978; see also, Yates, 1980).

In contrast, Homeokinetic theory employs the methodology of spectroscopy to index the cyclicity generated by thermodynamic engines. The test fields for homeokinetics range from biological cells to societies (cf. Iberall, Soodak, and Arensberg, 1980). Behavior of these systems is modelled by a set of scale independent formulations that relate kinetics/mechanics and thermodynamics in a *continuous*, *not* a *complementary* fashion.

4 THE NATURAL PERSPECTIVE: ECOLOGICAL REALISM

Broadly defined, the goal of a theory of perception and action is to explicate the co-ordination of animal and environment. Traditionally, the burden of the animal-environment co-ordination has been carried by a proposed medium of 'between things.' For example, in perception theory the proposed entities mediating animal and environment have been termed ideas, percepts, models, schemas, organizing principles, meanings, sense data, concepts and such like. John Locke's representational realism (Cornman, 1975; Mundle, 1971) formulated in the seventeenth century is the canonical version of perceptual theory in both its past and present forms (see Shaw and Turvey, 1981; Shaw, Turvey, and Mace, in press). Locke assumed that there was an environmental reality that existed independent of the act of perceiving but proposed that the animal was not directly in epistemic contact with that reality but rather with a representation of that reality, precisely, an *idea* that interfaced the animal as perceiver with the environmental object to which the animal's perception referred.

Among the many puzzles to which this view of perception gives rise, there is a particularly notorious puzzle that was a principal focus of Locke's critics, Berkeley and Hume, viz: what guarantees that the ideas (of which the animal is said to be directly aware) represent anything real. Berkeley thought a guarantee was unwarranted, and emphasized the phenomenalism (that there are *only* phenomenal objects such as ideas) implicit in Locke's theory; Hume thought a guarantee unlikely, and emphasized the skepticism (that there may be a real world but of its existence no-one can be sure) implicit in Locke's theory. For reasons that we will not go into here (but see Johnston and Turvey, 1980; Shaw and Turvey, 1981; Shaw, Turvey, and Mace, in press; Turvey and Shaw, 1979) the general argument that an animal is apprised directly not of the animal-environment system of which it is a part, but of phenomenal substitutes for that system (such as ideas) is a dubious starting point for scientific inquiry. For this latter reason and for others, it seems both judicious and prudent to pursue a realist posture, that is, to pursue tenaciously a reformulation of the logical and physical support of perception that deters regression to phenomenalism and skepticism. In short, to commit oneself to a style of inquiry that explicates animal-environment co-ordination without recourse to 'between things' (sometimes originating as analytic or methodologically useful terms but assuming, in the course of time, ontological status) so that science need not feel uncomfortable with the claim that animals perceive the reality that bears on their existence.

The aforementioned commitment to a realist philosophy is most obviously scale-sensitive: the reality that is relevant to animal activity and, therefore, the reality which is to be perceived, is at the scale of ecology and not, for example, at the scale of galaxies or atoms (Gibson, 1966, 1979). It is to an *ecological* realism, therefore, that the commitment is being made. In what follows, we summarize two themes of the ecological-realism program which bear prominently on the physical theory deemed appropriate for the ecological scale of nature: they are the doctrine of mutuality or synergy (with regard to the relation of animal and environment) and the doctrine of necessary specificity (with regard to the nature of information).

4.1 The Mutuality or Synergy Doctrine

Ecological realism rejects any variant of the traditional disposition to conduct animal-referential discourse and environment-referential discourse in two distinct and irreducible vocabularies, where matters of percieving and acting are at issue. That is to say, ecological realism rejects the disposition to describe animal and environment as apart from their joint operation or that each affects the other in the sense of causal interactionism (cf. Dewey and Bentley, 1949). The disposition to treat animal and environment as two parts of a dualism is at the core of the causal-chain theory of perception which attempts to trace a sequence of causes and effects between the environment described in physical terms, and percepts, described in mental terms said to be 'in' the animal. More prominently, for our current concerns, this disposition promotes dichotomies such as that of sensory processes (the consequences of which are described in mental terms) and motor processes (the consequences of which are described in physical terms), the central nervous system (described in a vocabulary appropriate to agents) and the skelotomuscular system (describable in a vocabulary appropriate to instruments), semantics (characterizations in intensional terms identifying what states of affairs *mean*) and syntax (characterizations in extensional terms identifying what states of affairs *are*) and, more generally, information and dynamics. When a system is conceptually severed in two and the consequences of the division held to be irreducible, one to the other, then a third kind of thing must be proposed to bring the separated things together when explanation so demands. Bluntly speaking, animal-environment dualism and its variants mandate 'between things' and repulse (ecological) realism.

Ecological realism starts with the assumption of mutuality or synergy of animal and environment (Gibson, 1979; Shaw, Turvey, and Shaw, in press; Turvey and Shaw, 1979). The animal and its environment are mutually constraining components of a single system (what might be termed an ecosystem) describable by a single vocabulary whose predicates are reflexive and symmetric. The animal is described in terms that reference the environment and the environment is described in terms that reference the animal. To paraphrase Dewey and Bentley (1949), the two terms, animal and environment, cannot be described apart from any joint operation as the two terms, matter and space, cannot be so described in the general theory of relativity. That the two terms, animal and environment, cannot be described in logically independent ways renders inappropriate attempts to co-ordinate them through causal interaction. The formula of causes and effects is, strictly speaking, a formula for binding mutually independent entities. That the two terms are mutually dependent renders unnecessary a third term to mediate them.

In sum, the mutuality of synergy doctrine deters partitioning complex systems (see Yates, 1980, for an informed account of the notion of complexity), of the kind that populate the ecological scale, into components that are described in logically distinct and irreducible vocabularies. A holding apart of information and dynamics, of semantics and syntax, of central nervous system and skeletomuscular system etc., is rejected by the mutuality doctrine, as are the correlated perspectives that any one component overseers any other and that any one component can be adapted to those states of another component that have yet to come into existence. On the positive side the doctrine promotes the idea of systemic components as mutually defined and mutually constraining, related acausally through symmetry principles (Shaw and Turvey, 1981).

4.2 The Necessary Specificity Doctrine

Let us turn to the second doctrine of the ecological realist program identified above, namely that of necessary specificity. Following the classical and conventional analysis of vision (which equates the optical support for vision with the inverted, metrically ambiguous and two-dimensional retinal image) it has been held quite generally, that the informational support for animal-environment co-ordination is imprecise, inadequate, and equivocal. The construal given to 'information' has been that of 'evidence,' in the sense of 'clues' or 'hints' about the environment and the animal's relation to it. That is to say, there is a generally accepted doctrine (indifferent to the sensory system of focus) that neither environmental objects and events, nor the perceiver's own movements, structure energy distributions in ways that are specific to their properties. Relatedly, a much-repeated argument has been that the energy distributions are meaningless because they are ambiguous, and because their description is in terms of variables of physics which make no reference to how a given animal can or should relate behaviorally to a given object. In brief, the informational support for animal-environment co-ordination is said to be non-specific to the states of affairs relevant to that co-ordination and, congruently, to be devoid of meaning. It should be underscored that here is encountered once again (2.0) the popular idea of 'information' as arbitrary with respect to the actions that it serves – that 'information' has a syntax but is not intrinsically meaningful; meaning has to be ascribed to the information base by an independent source.

Elsewhere the traditional and conventional conception of the informational support for perception and action has been termed the doctrine of intractable nonspecificity (Shaw, Turvey, and Mace, in press; Turvey and Shaw, 1979). Clearly, because this doctrine mandates 'between things' in the account of animal-environment co-ordination, the doctrine and, therefore, the view of information with which it is associated, must be rejected by ecological realism.

For any activity that an animal performs with respect to an environmental layout, information is needed about the nature of the layout, about the varying relations among the animal's body parts and about the changing relation of the animal to the layout (see Lee, 1976). If these kinds of information are impoverished and equivocal, the animal must embellish and disambiguate them; if they are arbitrary and meaningless the animal must interpret and ascribe meaning to them; and if they are defined over absolute (animal-neutral) dimensions, the animal must redefine them in body-scale terms (its own dimensions). Whenever any one of the above conditionals is accepted, ecological realism is infirmed. Therefore, the definition of 'information' for ecological realism mandates that information be unique and specific to the facts about which it informs, *meaningful* to the control and co-ordination requirements of the activity (what can be done, how it can be done, when it can be done) and *continuously scaled to the dimensions* of the system over which the activity is defined.

5 INFORMATION AS THE MORPHOLOGY OF DYNAMICS

Let us now see where the lengthy exegesis of the natural perspective has brought us. The overview of physical theory gives emphasis to the claim that the study of nonequilibrium systems will provide considerable insight into the evolution and functioning of living systems. Dissipative Structure theory and Homeokinetic theory both express the core thesis of such study, namely, that the flow of energy through a system, in the nonequilibrium thermodynamic sense, acts to organize that system; that the flow of energy is a self-organizing, self-complexing principle, and may be so at all physical magnitudes. A generalized energy flow system entails an energy source, an energy sink and an intermediate collection of operational components through which the energy flows. Under an irreversible thermodynamic analysis, the units of action at any scale must be energy flow systems – that is, they must be thermodynamic engines.

The overview of ecological realism denies the legitimacy of separating the animal and environment terms in such a way that a third class of terms has to be introduced to mediate them. Thus, explanation of the co-ordination and control of animal activity cannot be reduced to things which co-ordinate and things which control. Co-ordination and control refer to emergent states of the animal-environment system and not to mediating 'between things' (Fitch and Turvey, 1978; Gibson, 1979; Turvey, 1980). As anticipated in Section 1.3 and as expressed in Section 3.5, co-ordination and control are to be viewed as *a posteriori* facts resulting from distributed physical processes. The latter remark is equivalent to the claim that talk of information and dynamics cannot be conducted in two incompatible vocabularies. To reiterate, ecological realism denies a dualism of information (that controls and co-ordinates) and dynamics (that is controlled and co-ordinated). Fundamentally, ecological realism views information as arising in the dynamics of the animal-environment system, unique and specific to those dynamics and to the system's dimensions.

We can express this conception in another way that is perhaps more useful, given the general concern of the present paper with the problem of degrees of freedom. By the tenets of ecological realism there can be no such notion as an elemental unit of perception or action, from which other, more complex units, are constructed. The contrast of elemental (qua basic) with derived (qua complex) can have no place in explanations of perception and action, for it engenders 'between things' to 'put together' perceptions and actions. The information relevant to activity is not to be construed as elemental information associated with individual degrees of freedom which is somehow concatenated to give complex information associated with an ensemble of multiple degrees of freedom. Ecological realism prescribes that no matter how many degrees of freedom are involved in an action there will be an information base that is unique and specific to the ensemble; it anticipates that there will always be qualitative simplicity in the face of quantitative complexity; it allows that all informational predicates might be termed elementary but disallows that any can be termed elemental. These latter intuitions were prominent in Gibson's (1950, 1966, 1979) attempt to reformulate the optical support for vision through the notion of higher order variables or invariants. Following Gibson's lead, Runeson (1977) and Fowler and Turvey (1978) have remarked on the 'special purpose' nature of both information and a system's sensitivity to it.

Where might we find the confluence of the two themes of (i) energy flow as a self-organizing and self-complexing principle and (ii) information as unique and specific to an act, drawn as they are from the two respective branches of the natural perspective, physical theory and ecological realism? There are hints that the confluence is to be found in the morphology of the dynamics. The particular order exhibited by a thermodynamic engine depends in a very detailed way on the geometric properties that define the source-sink, energy-flow system (Morowitz, 1968). We noted in Section 3.5 that the geometry or form of the excess entropy production indexes points of stability around which the system organizes. The geometric properties are scaled to the dimensions of the thermodynamic system and are specific to its dissipative properties. Qualitative changes in the geometric properties of the excess entropy production function, pursuant to an excessive change in a system dimension, correspond to qualitative changes in the macroscopic properties of the thermodynamic system. We noted, in short, that the particular forms of a system's self-organizing and self-complexing are associated with the geometry of the energy fluxes.

We now move toward the following thesis: when energy is the dependent measure, transformations of a system (in terms of an activity) reveal dramatic gradients and equilibrium points. Sensitivity to the energy variable is synonymous with sensitivity to information specific to properties of the transforming system's dynamics. Furthermore, changes in the system's dimensions, incurred artificially or through growth, will result in a corresponding change in the gradients and equilibrium points revealed under transformation. In other words, *since the biological system of dynamics is functionally self-organizing (as argued in 3.0 above), then the corresponding system of gradients and equilibrium points (as information) is co-ordinately self-organizing.*

Let us consider how it is possible to construe these gradients and equilibrium points as the predicate types in which to characterize an information base. We do this in two steps: first, we consider the important distinction between essential and nonessential variables and second we consider those theoretical perspectives which attempt a qualitative characterization of systems whose quantitative characteristics are poorly known or resist calculation. The review that follows is historical in its organization. It attempts to put into perspective ideas that have been long present in the geometry of modelling and with which the theories of irreversible thermodynamics (Dissipative Structure theory and Homeokinetic theory) are continuous, viz., the emphasis on stability and the qualitative consequences of scale changes.

5.1 Essential and Nonessential Variables

The concept of gradients and equilibrium points as an information base stands in sharp contrast to the quasi-linguistic view of information as a finite sequence of letters taken from an alphabet and organized by a syntax; gradients and equilibrium points have their basis in an underlying 'organization' of geometric form. It is difficult to give a complete definition of this notion of organization; for present purposes let us settle on the equating of 'organization' with those characteristic features of a problem that facilitate obtaining a solution (Tsetlin, 1973). We will wish to say that the solution to the problem is achieved by taking advantage of the dynamic morphology of the problem itself. The problems of potential systems are considered 'well-organized' when the function can be partitioned into two classes of variables: essential and nonessential. Essential variables are geometrically defined as being capable of causing abrupt changes and discontinuities in the function's topological qualities (so, to conserve these qualities keep the essential variables fixed). Alternatively nonessential variables produce no qualitative changes in the function's topology but rather are capable of producing scalar changes over the topological qualities (so, to vary the topological qualities without annihilating them, allow the nonessential variables to change). Of significant importance is the fact that: (i) these characteristic features of organization *need not be known in advance* and (ii) *the partitioning of the essential and nonessential variables need not be fixed* (i.e. a continuous change along a dimension of a nonessential variable may cause an abrupt change such that a previously nonessential variable now becomes an essential variable or vice versa). Summing briefly, natural functions are well-organized when the variables may be partitioned into those variables capable of causing qualitative changes (i.e. essential variables) and those capable of causing quantitative changes (i.e. nonessential variables).

The behavior of essential and nonessential variables is distinguished mathematically in the behavior of nonlinear and linear variables respectively. The concept behind the distinction is best appreciated in terms of the operational transformations induced from one vector space to another. In the mapping from one vector space to another, from 'input' to 'ouput,' the behavior of a linear system is characterized by the properties of 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, $L(X_1 + X_2 \ldots + X_n) = L(X_1) + L(X_2) + \ldots + L(X_n)$. 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, $L(\alpha X_1, \alpha X_2 \ldots \alpha X_n) = \alpha L(X_1, X_2 \ldots X_n)$. In brief, variations in the 'domain' are precisely captured by variations in the codomain. Put differently, the degrees of freedom specified in the 'input' are identical with the number of degrees of freedom in the 'output.'

In contrast, variations in the domain of a nonlinear system are not associated with linear variations in the codomain. The properties of proportionality and superposition are not preserved in nonlinear systems. Nonlinear systems are characterized by inhomogeneities in the codomain where the inhomogeneities identify 'preferred' locations on which the system tends to converge. Variation on the micro scale of 'individual' system parameters (the domain) are not continuously (that is, linearly) associated with changes in the macro scale of systemic parameters (the codomain). Changes in the macro systemic parameters are only realized when critical ratios occur relating individual system parameters on the micro scale. When these ratios are achieved the systemic behavior of the system moves from one stable mode to another (as indexed in the codomain mapping).

One final contrast needs to be drawn. The distinction between nonlinear and linear is a *formal* mathematical distinction; that between essential and non-essential 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 resolution power, the self-sensitivity, of the system (Kugler, Kelso and Turvey, 1980).

As a relevant aside, it was to Bernstein's credit that, in his later writings, he gave full recognition to the essential/nonessential distinction as an appropriate way to characterize living systems. Bernstein too was impressed by the fact that many living things embody the features of 'well-organized' functions. Just as the leaves of a tree are never exactly alike in their metrical, nonessential dimensions yet still possess the essential qualitative characteristics of the particular type of tree to which they belong, so the various acts that people perform (e.g. handwriting, gait, piano-playing) retain their essential and individualistic properties over marked variance in nonessential variables (see Kelso, 1981; Kugler, Kelso, and Turvey, 1980) for many examples in the motor system's literature). There are strong hints in Bernstein's later writings of a dissatisfaction with the 'artificial' perspective of cybernetics, with its search for analogs between manmade machines and living systems. In the theory of well-organized functions that applies to the antientropic processes of open systems, Bernstein (1967) foresaw the end of the 'honeymoon' (p. 181) between the sciences of cybernetics and physiology. In short, in the class of natural functions that envelop the behavior of systems with many degrees of freedom, Bernstein envisaged an opportunity to model 'the basic forms of real, not fictitious, life processes' (p. 186).

5.2 Qualitative Characterizations of Systems

5.2.1 Geometric Similarity

Qualitative characterizations of systems are historically based in Euclid's (300 BC) principle of geometric similarity. Geometric figures were said to be *similar* if they shared the same shape but not necessarily the same size. Preservation of both shape and size meant that the two objects related not only similarly but also congruently. For Euclid similarity was a qualitative measure whereas congruence was a quantitative measure. The principle of similarity formed the basis for one of the earliest theories of modeling.

In general there is a point-to-point correspondence between a model and its prototype. In geometrical terminology, two points that correspond to each other are *homologous*. The concept of homologous points leads immediately to the concept of homologous figures and homologous parts. Figures or parts of the model and the prototype are said to be homologous if they are comprised of homologous points. If transient (i.e. time-variable) phenomena occur in a model, it is necessary to introduce the concept of 'homologous times.' For Euclid, however, geometric similarity was concerned only with the relation between homologous parts. Two systems were said to be *geometrically similar* if homologous parts of the systems were in a constant ratio. Any deviation from the above restriction would annihilate or distort the shared set of geometric qualities.

5.2.2 Dynamic Similarity

Extending the principles of similitude from geometric to dynamic systems, Galileo (1564–1642) formulated the first principle of dynamic similarity. Two systems were said to be *dynamically similar* if homologous parts of the system experienced similar net forces. The principle of dynamic similarity was a special case of the general conception of geometrical similarity. If two systems of connected particles and rigid bodies were geometrically similar, additional relationships were required to make them dynamically similar. The two systems were said to be dynamically similar if, in addition to the constant ratio between the linear dimensions, the masses of corresponding portions bore a certain ratio, and the rates of work at corresponding points also bore a certain ratio. It then followed that the forces at corresponding points related as a certain ratio dependent on the other three ratios.

5.2.3 *Kinematic Similarity*

The first principle of kinematic similarity was formulated by Newton (1642–1727). Kinematics is the theory of space-time relationships, consequently kinematic similarity signifies similarity of motions. Two systems are said to be *kinematically similar* if homologous parts of the system lie at homologous points at homologous times. Thus two systems that are kinematically similar have corresponding components of velocity and acceleration that are similar. If kinematically similar systems also share similar mass distributions, they are also dynamically similar.

The above principles of similarity are the basis for modeling methods that allow for the preservation of certain qualities (geometric, kinematic or dynamic) without requiring any exact specification of numerical numbers. Qualitative properties are preserved by virtue of maintaining critical ratios invariant from the prototype to the model. We described this method of modeling in Section 1.2 under its more general label of *dimensional analysis*. Recall that it allows for the specification of similarity between two systems by merely analyzing certain *dimensionless numbers* (like a Reynolds' or Rayleigh number) formed by the required ratios.

5.2.4 *Qualitative Dynamics*

Towards the end of the nineteenth century Poincaré proposed a more abstract characteristic of qualitative properties. By linking calculus and topology, Poincaré conceived of a new qualitative study of differential equations (i.e. $dx/dt = f(x)$), called *qualitative dynamics*. Poincaré found that even if quantitative solutions were impossible, it was still possible to derive qualitative information. For example, qualitative statements such as 'the solution is periodic' were readily revealed, whereas quantitative statements such as 'the solution has a period of 2.5432' were not available without elaborate computational procedures. In fact exact quantitative solutions often defy computation. Using the methods of differential topology, Poincaré could identify the qualitative properties of dynamic systems (e.g. periodicity, equilibrium points, types of stable regions, etc.). Whereas the earlier Principles of Similitude were based in a theory of modeling (preservation of a given set of qualities from a prototype to a model), Poincaré's theory of qualitative dynamics was concerned with a theory of design (understanding the nature and origin of the qualitative properties within a system).

5.2.5 Growth and Form

Based on an appreciation of qualitative dynamics and the earlier principles of similitude, Thompson (1917) proposed a unified theory of *growth and form.* With reference to design, Thompson argued that the form an object takes on is intimately linked to the dynamic properties of stability. Moreover, stability was not to be understood merely as the sum total of interacting forces, but rather required a close examination in terms of the qualitative properties inherent in the system's geometry. The exact nature of these stabilities, however, eluded Thompson's mathematics. In terms of modeling, once the qualitative properties were manifest by the system, various transformations (affine, shear, cardiodal, etc.) could be imposed on the system without annihilating them. Growth was explained as a modeling process in which certain qualitative properties were preserved under continuous transformations. This allowed for an explanation of how systems grew and still maintained certain kinematic, geometric, and dynamic similarities. Thompson suggested that the similarity in forms between animate and inanimate systems was the result of the systems sharing similar stable configurations. In short, the fundamental nature of stable configurations is insensitive to material composition. Whether a cloud in the sky or an amoeba in a pond, the qualitative form realized by these dynamic structures is understandable as a stable configuration. Force and material composition can only affect the form in the quantitative fashion of similarity transformations.

5.2.6 Relational Biology

A little later, Rashevsky (1938/1950) was to postulate a theory of *relational biology* based on the qualitative properties of functions. Rashevsky's interest was primarily in a theory of design. His insight was the recognition that what biology is directly interested in is primarily dynamic function and behavior and not static structure. On the other hand, it is structure that we can most readily study quantitatively. The two are related, in traditional reductionist terms (as contrasted with the newer version described in 3.6) by the view that 'structure implies function.' As Rashevsky opined, however, even if a reductionistic approach to the study of dynamic systems was in principle correct (which he doubted), that might be the hard way to go about the task. What he attempted to do was to create a mathematical framework in which function, organization, and behavior could be directly characterized and studied apart from any material or structural basis. Through an understanding of qualitative properties of functions, Rashevsky hoped to gain insight into the corresponding organizational constraints manifest in a behaving system. Relational biology was grounded in the realization that the qualitative properties of a function could be expected to place corresponding quantitative constraints on the organization of biological systems.

5.2.7 Catastrophe Theory

More recently, Thom's theory of catastrophes (1970, 1975) offered the most formal analysis of qualitative complexity in dynamic systems. Thom's goal in catastrophe theory was to describe the origin of dynamic form, that is, morphogenesis (see Waddington, 1970, for variations on the use of this term in modern biology). Following almost explicitly the arguments of Thompson (1917/1942) Thom used the techniques of Poincaré's differential topology to provide the needed mathematical justification. By giving up quantitative concepts, the topologist gains the ability to analyze certain abstract properties of a function's form. For a problem involving dynamic variables, topological qualities such as equilibrium regions are of crucial importance and may be readily revealed using the techniques of differential topology. The ability to reveal these qualitative properties, however, is only achieved by giving up quantitative concepts such as rate, distance, and magnitude. This allows a topologist to search multidimensional spaces for equilibrium regions with relative indifference to any quantitative measures. The arena of multidimensional spaces with their various equilibrium points constitutes the basic material for Thom's theory of catastrophes.

Essentially, Thom created a mathematical language – catastrophe theory – built on the assumptions of structural stability and qualitative regularity. He proposed that the development of form was completely 'independent of the substrates of form and the nature of forces that create them' (1975, p. 8). Furthermore, 'the only stable singularities are determined solely by the dimensions of the ambient space' (1975, p. 8). In short Thom proposed a theory of form based principally on an appreciation of potential stable points, where these stable points are specified by the dimensionality of the space. The properties of force and material substance are primarily associated with scalar transformations (affine, shear, cardiodal, etc.) on the system's stable dynamic form. Due to the abstract nature of form and stability, the same set of stable points could be manifest by a wide variety of systems. Once again, this commonality could account for the wide similarity in form between many animate and inanimate systems. Because of this fact Thom argued, as Thompson had earlier, that a qualitative study of form should proceed from the mere study of force and substance to the abstract study of form itself. In this regard, Thom moved from the methods of conventional stability theory to the theory of structural stability.

5.3 Stability and Catastrophe

Conventional stability theory centers on understanding the dynamical properties associated with certain systems of differential equations. The stability associated with these systems is often represented by the analogy of a marble rolling on a surface (see Figure 5). The system is *stable* if the marble ultimately returns to its initial equilibrium point after a perturbation has been introduced (upper panel of Figure 5). More formally, this stability is referred to as 'point' stability. Conversely, the system is *unstable* if the initial perturbation response does not die away, corresponding to the marble being displaced from the top of the hill (middle panel of Figure 5). Finally, there is *neutral stability* as exemplified by the marble on a flat surface (lower panel of Figure 5). Following initial perturbation the system remains in a new condition dependent on the parameters of the perturbation. This system does not exhibit any tendency systematically to return to or deviate from the initial conditions.

A richer set of building material for dynamical landscapes than the simple hilltops and valley bottoms associated with conventional stability theory is

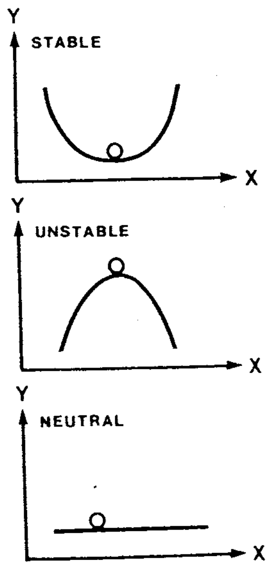

FIGURE 5 Dynamical modes associated with conventional stability theory (see text for details)

found in the theory of structural stability (cf. Thom, 1975). The theory of structural stability seeks to understand qualitative changes in a system's dynamical character as various independent parameters (which serve to define the dimensions of a system) are changed. Whereas conventional stability theory deals with local response patterns to perturbations, structural stability theory deals with global changes in the dynamical landscapes.

A system of differential equations is referred to as 'structurally stable' if the dynamical landscape remains qualitatively unaltered in the course of changes in the independent parameters. This region of stability may be likened to the similitude region referred to in 1.2, as a *preservation* of qualitative form over a scaling-up in magnitude. At critical scale changes, however, dramatic qualitative changes in the landscape can occur – for example, when a peak and a valley coalesce in mutual annihilation. This region of instability may be likened to the dissimilitude region referred to in 1.2, a *change* in qualitative form over a scaling-up in magnitude. These instabilities are marked by a continuous variation in an independent variable being associated with a discontinuity on a more macro description (such as in the landscape or behavioral descriptions). In these critical regions continuous changes in micro variables which define the system's dimensions may suddenly become associated with dramatic 'jumps' in a system's description on a more macro level. The sudden transition or jump appears to be discontinuous not because there are no intervening states or pathways, but because none of them is stable; the passage from the initial state to the final one is likely to be brief in comparison to the time spent in the stable states. Thom's theorem of 'elementary catastrophes' describes the seven simplest ways for such transitions to occur. According to the theorem, the types of catastrophes which may be associated with a particular system are finitely bounded by the system's dimensionality. In short, each dimensional system has a distinct number of catastrophes associated with it (for example, there are seven distinct catastrophes or bifurcations associated with a system with four dimensions, see Thom, 1975).

The importance of Thom's 1975 discovery was that not only were these patterns of behavior conditioned solely by the system's dimensionality, but they were also limited to a very small number of possibilities. What Thom had formally proven was that as a system increased its organizational complexity the posssibility of increased qualitative complexity was limited. Furthermore, the nature of the qualitative complexity was indifferent to the material substance. In essence Thom was demonstrating the prohibitiveness of multiple solutions to recurring problems in nature. For example, the biological heart and the technological pump are functionally equivalent in terms of pumping fluids; the biological lungs and the blacksmith's bellows are functionally equivalent in terms of pumping of air; and the bacteriophage and the syringe are functionally equivalent in terms of the injecting fluids into and withdrawing fluids from a cavity. Several more general solutions are evident in the problem of locomotion and grooming. Regardless of the species, the solutions to these two problems appear to be fixed. For locomotion, the dynamic relationship between the swing phase and stance phase remains invariant over all locomoting species (Pearson, 1976). Similarly, for grooming, there are strong hints that the temporal relationship among the phases of grooming remains invariant over all grooming species. In short, from Thom's perspective, the functional similarity in the structuring of many natural problems is owing in large part to the limited number of stable possibilities. (And this, we should suppose, is the conceptual backdrop befitting Baerends' (1976) intuition that the phenomenon of convergence – where the same function is seen in largely disparate species – reflects the fact that the solutions to the design problems for living systems extend in age beyond species, families, and even phyla.)

We conclude our brief discussion of stability and catastrophe with a few cautionary notes. Thom's theory of catastrophes provides us with a complete classification of transitions that may occur at points of structural instability. Unfortunately the theory is limited to systems with a finite number of degrees of freedom described by ordinary differential equations. This is a nontrivial restriction because most natural systems involve both spatial and temporal parameters and thus are governed by partial differential equations with an infinite number of degrees of freedom. At present, however, there is no comprehensive theory for the solution of nonlinear partial differential equations (cf. Nicolis and Auchmuty, 1974).

5.4 The Principle of 'Order Through Fluctuation' Revisited

From bifurcation and catastrophe theory we learn that scale changes over particular parameters of dynamic systems are sufficient to induce instabilities in the macro structure; ultimately, the instability leads to a higher order of qualitative complexity. What we fail to gain from these theories, however, is an account of the mechanism responsible for inducing the onset of the instabilities. With reference to this issue we re-examine Prigogine's (1976) principle of 'order through fluctuation.'

From our earlier discussions of irreversible thermodynamics we derived the following claim: if systems of any kind are in a sufficiently nonequilibrium state, have many degrees of freedom, have nonlinear components and are open to the inflow of energy and matter, the ensuing instabilities do not lead to random behavior; instead, when critical scale changes are realized the system is suddenly driven to a new stable regime which corresponds to a new state of qualitative complexity. In such transitions the system acquires new margins to produce entropy, new possibilities for activity. We noted above that a closed equilibrium system, with a monotonically increasing entropy function, is

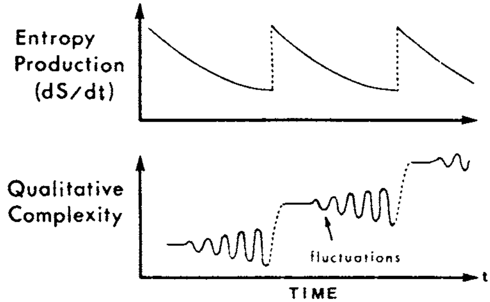

FIGURE 6 Amplified phase of fluctuation

characterized by decreasing activity and entropy production. As it approaches maximum entropy, which corresponds to the lowest state of order, the system asymptotes onto a reversible equilibrium condition. A partially open equilibrium system, in contrast, moves through a sequence of transitions to new regions which, in such cases, generate the conditions of renewed high entropy production within the new regime (see Section 3.5), and thus opens up the possibility for the development and maintenance of new qualitative complexities (see Figure 6).

Prior to realization of a critical scale change, systematic or random fluctuations are asymptotically damped to the previous steady-state condition (see Figure 7). Upon achieving the transition threshold the previously damped fluctuations now amplify and drive the system to new stable regimes. It is also possible for systems close to but below the critical ratio to reach the unstable transition region when certain types of fluctuations are present (cf. Prigogine and Nicolis, 1973). In either case the amplification always occurs in the fluctuation, driving the system to new stabilities. The source of the fluctuations – the spontaneous deviations from some average regime – are a universal

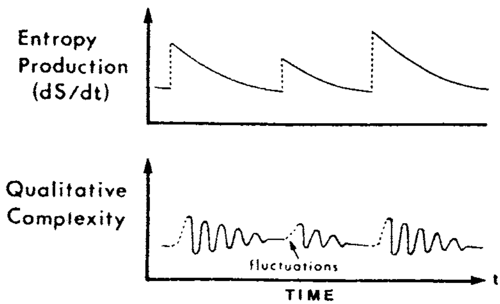

FIGURE 7 Damped phase of fluctuation

phenomenon in systems with large numbers of degrees of freedom (Prigogine, Nicolis, and Babloyantz, 1972).

Let us consider briefly the systematic events associated with the two phases of fluctuation: damped and amplified. Damped fluctuations are associated with thermodynamic systems possessing large numbers of degrees of freedom. The macro behavior of these systems may be said to be determinate since the damping continuously returns the systems to the same steady-state condition. As the thermodynamic system approaches the transition threshold, common fluctuation frequencies emerge allowing for the possibility of entrainment. Previously damped fluctuations are now amplified into a few 'preferred' frequencies. As the operational components are entrained, systematic dissipation of degrees of freedom occurs. Ultimately as the system moves through the critical region, the operational system of many degrees of freedom entrains into an ensemble system exhibiting a single degree of freedom. (This evolutionary sequence is consistent with Iberall's organizational principles for complex physical systems, see Section 3.6.) Prigogine and his colleagues (Prigogine, Nicolis, and Babloyantz, 1972) summarize the above events as follows: 'In the neighborhood of a stable regime, evolution is essentially deterministic in the sense that small fluctuations arising are continuously damped. But near the transition threshold the evolution becomes a stochastic process in the sense that the final state will depend on the probability of creating a fluctuation of a given type. Of course, once this probability is appreciable, the system will eventually reach a unique (apart from small fluctuations) stable state, once the boundary conditions are specified. This state will then be the starting point for further evolution' (p. 27).

5.5 Co-ordinative Structures as Dissipative Structures

Let us now draw these arguments to a conclusion by returning to Bernstein's problem concerning the regulation of biomechanical systems possessing multiple degrees of freedom. It has been argued by Bernstein (1967) and those who have pursued his point of view (e.g. Gelfand *et al.*, 1971; Greene, 1972; Turvey, 1977) that the problem of degrees of freedom may be 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. A muscle linkage or a *co-ordinative structure*, as we have come to call it (Kelso *et al.*, 1980; Kugler, Kelso, and Turvey, 1980; Turvey, Shaw, and Mace, 1978) is a group of muscles often spanning a number of joints that is constrained to act as a single functional unit. We have argued elsewhere both theoretically (Kugler, Kelso, and Turvey 1980) and experimentally (Kelso *et al.*, 1980) that a co-ordinative structure is a member of the class of thermodynamic engines qua dissipative structures, and that by virtue of this membership a principled basis is provided for understanding movement co-ordination and control.

A co-ordinative structure as dissipative structure differs from traditional concepts in the motor systems' literature (such as servomechanisms and programs). Instead of pre-established arrangements among components or ordered arrangements of specific instructions, co-ordinative structures constitute a set of organizational constraints which emerge as a function of various energy transactions, and scale changes at multiple levels of organization (ranging from motor units to muscles). Emerging constraints form a dynamic manifold of gradients and equilibrium points. The 'layout' of the manifold *uniquely* and *specifically* indexes biomechanical configurations in terms of *stability* and *energy dissipation.* An important features of the manifold is that it provides an information basis that is continuously scaled to artificially or naturally incurred changes in the systems' dimensions. As an information base the manifold does not 'cause' behavior to occur, but provides continuous information *about* the state of potential dynamic configurations. A manifold is 'structurally-stable' if the topological properties which define the manifold remain unaltered under a range of scale changes in the system's dimensions. Under such conditions the system will continue to exhibit the same set of stable biomechanical configurations. In the event that a scale or dimensional change causes a qualitative change in the manifold's topology – as when a topological property (such as an inflection point) is created or annihilated – then a new set of stable biomechanical configurations may arise. In Thom's terminology, a catastrophe has occurred in the system in the form of a sudden instability in the structure of the dynamic manifold. The catastrophe or bifurcation is always a function of changes in scale or dimensionality.

Let us examine several examples of motor behavior in which a bifurcation occurs in the structural stability of the biomechanical system. Consider the problem of quadruped locomotion. At low velocities, all quadrupeds locomote with a common asymmetry of limbs of the same girdle – they are always half a period out of phase. As the animals scale-up on velocity there is an abrupt transition from an asymmetric gait to a symmetric gait (Shik and Orlovskii, 1965). At higher velocities the stable states of quadruped locomotion are characterized by an in-phase relation of limbs of the same girdle (Grillner, 1975). Sudden changes in biomechanical stabilities wrought by changes in scale and dimensionality are also captured in centipede locomotion. The *Lithobius* normally moves its legs in waves with adjacent legs out of phase by one-seventh of a step. If, however, all but two pairs of the legs are amputated – and regardless of the number of segments separating the pairs – the insects will now display the asymmetrical gaits of quadrupeds. Similarly, *Lithobius* displays the gaits of six-legged insects when all but three pairs of legs are amputated (von Holst, 1973). A final example is drawn from the biomechanics of dolphin locomotion (Brookhart and Stein, 1980). At low velocities the dolphin's swimming pattern can be described as oscillatory. The motion creates a laminar flow of water over the dolphin's body surface allowing a stable form of travel in which energy dissipation is minimally incurred. At higher velocities, however, the laminar flow of water suddenly turns to turbulence. The earlier mode of travel has now become unstable and very expensive in terms of energy dissipation. At this point the dolphin abruptly changes its swimming mode to a more stable form of 'running' in which it periodically leaves the surface. This novel mode of travel now indexes a biomechanically stable solution for the new velocity.

The above examples are meant to emphasize the role of dynamics in the forging of spatiotemporal orderings in biomechanical systems. From this perspective a co-ordinative structure as dissipative structure interprets different locomotory gaits as those stable movement patterns, few in number, that can arise pursuant to the instabilities wrought by scaling-up muscle power (Kugler, Kelso, and Turvey 1980). The general point here is that locomotory patterns are to be explained by an appeal to the concepts and tools of nonequilibrium thermodynamics such as stability theory, bifurcation theory, and fluctuation theory (Haken, 1977; Prigogine *et al.*, 1975; Thom, 1975) rather than an appeal to formal programs of instructions or sets of anatomically fixed constraints.

5.6 Co-ordinate Structures as Dissipative Structures: Developmental Comments from the Perspective of Stage Theory

Throughout this chapter our paradigm issue has focused on how it is that the body's many degrees of freedom can be systematically regulated in the face of scalar changes in the body's dimensions. As we have noted earlier, solutions to the degrees of freedom problem cannot be impervious to the Principle of Similitude. Just as a movement's topological qualities remain stable in the face of quantitative changes in scale, so also does scale induce qualitatively different movement patterns. In the previous section – and elsewhere – we have identified these features of movement with co-ordinative structures, and stressed the theoretical and empirical relationship between co-ordinative structures and dissipative structures (cf. Kelso *et al.*, 1980; Kugler, Kelso, and Turvey, 1980). Here we wish to recognize the large body of descriptive data in motor development – as yet unevenly rationalized – and show that it is consistent with the notion of co-ordinative structures as dissipative structures.

There is collective agreement among developmentalists that as a child grows and develops, movement organizations change in a qualitatively step-wise or 'stage-like' fashion (e.g. Roberton, this volume; Smoll, this volume). Although the stage notion is used with varying degrees of sophistication, its universal connotation is one of sudden qualitative changes in the spatiotemporal orderings of behavior that occur as a consequence of developmental age. With respect to movement development, the categories that constitute 'stages' are derived empirically according to descriptions of movement patterns – usually observed in natural settings. Even though a descriptive analysis may have predictive value – as in the mapping of 'motor milestones' (e.g. Bayley, 1935; McGraw, 1941, 1945) – it lacks explanatory power. Indeed it is crucial for present purposes, to recognize (as so many have, cf. Connolly, 1970) that the descriptive approach is neutral with respect to the question of underlying *process*. We offer here an account of such processes in terms of the theory of co-ordinative structures as dissipative structures.

The data base that we shall consider is provided by the detailed longitudinal descriptions of how movements of an individual change over time (see Halverson and Roberton, 1966; Halverson, Roberton, and Harper, 1973). We refer specifically to the intra-task changes in the overhand throw for force (see Roberton, 1978 and this volume). Figure 8 illustrates the 'staircase' development of the forearm action in one child from the age of around 2 years to 13 years. The developmental 'steps' correspond to (i) no forearm lag, (ii) partial forearm lag and (iii) full forearm lag (see Roberton, 1978 for details and methods of analysis). This diagram serves to illustrate a stable sequence of spatiotemporal patterns associated with intra-task development as a function of time. The sequence is characterized by a series of qualitatively distinct patterns that are relatively uniform for all subjects despite individual differences in age of occurrence. Note that a relatively short period of time is spent in the transition or unstable period of development, while stable organization (as reflected in plateaus) is maintained for much longer. In contrast, Figure 9 illustrates a case where the instability – as indicated by the prolonged period of fluctuation – occurs over a longer period of time. How might these qualitative changes in movement patterns that develop over time (and take various forms) be interpreted?

The central claim throughout the present paper is that we should construe the development of self-organizing systems as an evolution of a dynamic geometry whose structure is created and maintained by a thermodynamic engine. In addition, we have proposed that information might best be conceived as form. Equilibrium points and gradients emerge from such a proposal as the fundamental building material for a manifold which relates to the evolving system in a unique and specific fashion. Sensitivity to properties of the manifold is synonymous with sensitivity to information *about* the *state* of the system's dynamics. The structural properties of the manifold are created and maintained by a continuous flow of energy into and out of the operational components of the system. Under certain scale changes the dynamic qualities of the

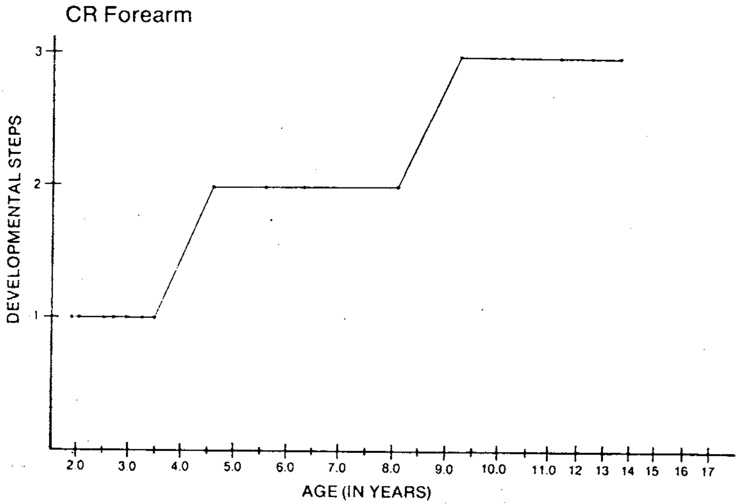

FIGURE 8 'Staircase' development in overarm throw forearm action in child CR (male) from age 1-10 to 13-2 years. Developmental steps are (i) no forearm lag; (ii) partial forearm lag; and (iii) full forearm lag. (See Roberton, 1978a for complete category descriptions.) Reprinted with permission from Roberton, M. A., and Langendorfer, S., Testing motor development sequences across 9–14 years, In K. Newell, G. Roberts, W. Halliwell, and C. Nadeau (Eds.), *Psychology of motor behavior and sport – 1979*, Champaign, Ill.: Human Kinetics. 1980
(Figures 8 and 9 correspond to Figures 1 and 2 of Roberton (this volume). We are very grateful to Mary Ann Roberton for allowing us to display them here which we do for the sake of completeness.)

system will remain invariant, while under critical scale changes the previously stable organization of the manifold may suddenly break down and be replaced by a new organization. The important feature of this sequence of events is that a *continuous* change in a single variable (or combination of variables) may bring about a sudden *qualitative* change in the macro structure of the manifold associated with the variable(s). The qualitative changes in the manifold reveal themselves in the annihilation or creation of various equilibrium points.

The above explanation of 'stages' of development is obviously conjectural at this point. But let us offer some suggestions as to how these claims might be formalized. The first step in any stage theory of development is to distinguish the various stabilities and instabilities associated with the developmental sequence of interest. Traditionally the descriptive criteria for identifying various stages have suffered from a rather subjective origin. Certain landmark features are selected which purportedly distinguish one stage of development

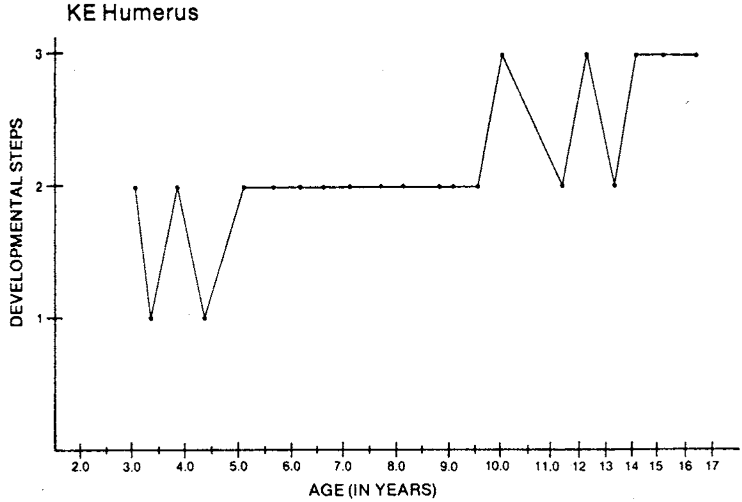

FIGURE 9 Step-to-step development in overarm throw humerus action in child KE (female) from age 3-0 to 16-3 years. Several years of transition occurred before reaching each higher level. Developmental steps are (i) humerus oblique; (ii) humerus aligned but independent; and (iii) humerus lags. (See Roberton, 1978a for complete category descriptions.) Reprinted with permission from Roberton, M. A., and Langendorfer, S., Testing motor development sequences across 9–14 years, in K. Newell, G. Roberts, W. Halliwell, and C. Nadeau (Eds.), *Psychology of motor behavior and sport – 1979*, Champaign, Ill.: Human Kinetics, 1980

from another in an unambiguous way. In general the criteria are motivated by methodological concerns. A more theoretical criterion for selecting different stages might be found in the principles of homeokinetic physics (see Section 3.6). Recall that homeokinetic physics seeks to provide a physical account of the orderly events associated with biological systems. Homeokinetics argues that a thermodynamic engine defines the minimum unit of biological organization. Energy transactions within the thermodynamic engine are always in the form of limit cycle oscillation. The unit of organization may vary in size and order of complexity. A simple unit of organization might constitute a single sink–source, energy-flow system. A more complex system might constitute a collective of sink–source, energy-flow systems which interact in a unified manner so as to exhibit a single collective limit cycle oscillation. An example of a simple system might be a single cell whereas a complex system might be an organ composed of many single cells. In both cases, however, the behavioral unit of organization is an autonomous thermodynamic engine and may be functionally distinguished by the unique spectral properties of the system's limit cycles. Thus, various units of organization may be systematically distinguished in terms of their spectral properties (see Section 3.6.2 for the homeokinetic methodology).

If the limit cycle signature is to be of any use in distinguishing stable patterns of movement organization, then the movement patterns must be chosen with concern for dependent measures which are sensitive to spectral properties. Such movement patterns would require a degree of rhythmicity in their fundamental form (although note that the choice of rhythmical activity is methodologically motivated; elsewhere we have shown how discrete and cyclical movements could emerge from the same limit cycle organization (Kelso *et al.*, 1980; Kugler, Kelso, and Turvey, 1980)). Stable patterns of movement could then be distinguished in terms of their spatiotemporal properties. In short, a methodology based on homeokinetics would entail selection of behavioral sequences which distinguish themselves developmentally in terms of their spectral composition. Such patterns may well share or be elaborations of certain biomechanical configurations that developmentalists have traditionally associated with stages. The point to emphasize however is that the homeokinetic methodology offers a theoretical basis for selecting sequences of stable biomechanical configurations that may constitute developmental stages.

A second methodology for distinguishing various stages of organizational development may be borrowed from Dissipative Structure theory (see Section 3.5). The methodology of dissipative structures entails an identification of the kinetic equations which describe the bifurcations of the biomechanical stabilities associated with scale changes. While homeokinetics focuses on the maintenance of stable organizations, the second methodology – from Dissipative Structure theory – addresses the instabilities associated with transition phenomena. For critical values an instability can arise that causes the biomechanical configuration to change radically and in a discontinuous manner. The beginning of an approach based on dissipative structures starts with an identification of the dimensions which define the system of interest. For the biomechanical system this involves variables such as mass, length, stiffness, etc. Unfortunately even when the dimensions are known, formulation of the appropriate equations can still constitute a formidable task. Such an analysis, we suspect, would allow deep insights into which variables are most critical at which periods in time (see for example, Kugler, Kelso, and Turvey, 1980, Figures 8 and 9).

6 A PHYSICAL AND EPISTEMOLOGICAL BASIS FOR DESIGNING AND MODELING NATURAL SYSTEMS: A SUMMARY

The principal goal of this chapter has been to discuss the physical and epistemological basis of order and regularity in natural systems. We have proposed a perspective on the analysis of natural systems that is characterized by a commitment to two coupled themes: first, an explanatory commitment to physical theory, and second, an ontological and epistemological commitment to the tenets of Ecological Realism. The perspective follows the lead of Iberall, Yates, and Soodak in seeking a universal set of design principles that can be applied repetitively and with equanimity across all scales, and across all disciplines that address systematic phenomena in biology.

A major problem confronting theories of biological organization concerns the provision of a principled account of the systematic reduction in a system's potentially large number of degrees of freedom. More formally, the problem focuses on the systematic mapping from a space of multiple fine-grain variables to a space of considerably fewer coarse-grained variables. In terms of movement science the problem is realized in the stable organization of gross movement patterns of a very few degrees of freedom which are derived from a skeletal basis of very many degrees of freedom. The solution outlined in this chapter is derived from many principles that are not commonplace to students of the development of movement. Such principles originate in philosophy, physics, biology, engineering science and, in particular, nonequilibrium thermodynamics and the ecological approach to perception and action. Throughout, our paradigm issue has been the developmental implications of scale changes in the body's dimensions, and the problem of how information can be conceptualized so as to insure continuous control and co-ordination in the face of such scale changes. Below is a summary statement of the physical and epistemological principles implicated in a theory of the control and co-ordination for naturally developing systems. We begin with a summary of physical principles.

6.1 Physical Principles That Inform Biological Design

According to classical physical theory (or at least its philosophic view) living systems were viewed as continuously struggling against the laws of physics. The temptation was to ascribe an accidental character to living processes and to imagine their origin as a result of a series of highly improbable events. Indeed, living systems were viewed as the consequence of biological principles that were independent of the laws of physics. The account currently emerging in the field of molecular biology and nonequilibrium thermodynamics supports a different point of view. Far from being outside physical laws, living processes are viewed as following from the laws of physics whenever certain open conditions prevail. The principal results in favor of this conclusion are as follows: systems close to equilibrium always turn toward equilibrium in a linear fashion and evolve to a disordered state corresponding to the steady state of equilibrium. Small deviations, due, say to random perturbations, are continuously damped out by a mechanism ultimately operating on a variational principle of minimum entropy production. The mechanism operates such that for time-independent boundary conditions, the dissipation inside the system (measured by the production of entropy per unit time) attains a minimal value compatible with boundary conditions. If the system is open to the flow of energy and matter, then it is possible to increase its operating distance with respect to global equilibrium. As the distance increases the steady state close to equilibrium continuously shifts up a thermodynamic branch of states, all of which exhibit linear stability of the equilibrium-like behavior. The equilibrium structures which constitute the thermodynamic branch are obtained through a continuous modification of the boundary conditions. As the distance from equilibrium is scaled-up, a critical point is reached where the damping mechanism suddenly breaks down due to nonlinear interactions. No longer does the linear damping mechanism guarantee the global stability of the branch; the disequilibrium state becomes unstable, the amount of dissipation introduced by the fluctuations becomes negative, resulting in amplification rather than damping of the fluctuation. The resulting instability drives the system off the thermodynamic branch (globally but not locally) to a qualitatively new spatiotemporal structure that exhibits the characteristics of nonlinear limit-cycle stability.[1]

An important characteristic of the instabilities is that the relation between order and fluctuation is much more complex than at equilibrium. At equilibrium everything is determined by the strict properties of the thermodynamic potentials and hence the fluctuations are all damped in a characteristically similar manner. This is not the case in the nonlinear range where not only are fluctuations the trigger for the appearance of new structures and processes, but different types of fluctuations may also correspond to different structures. To emphasize the role of fluctuation, Prigogine has termed the new ordering principle *order through fluctuation*.

Two developmental phases may be distinguished. The first phase corresponds to the emergence of a qualitatively new ordering in the macro structure. The second stage entails the stable maintenance of the new structure. The creation phase is associated with *a theory of design*; that is, a theory implicating *change* in various qualitative properties from one system to another. The maintenance phase, on the other hand, is associated with *a theory of modeling*; that is, a theory implicating *preservation* of various qualitative properties from one system to another. The two phases distinguish themselves thermodynamically in the behavior of entropy production: the creation phase operates on the variational principle of excess entropy production, while the maintenance phase operates on the variational principle of minimum entropy production. In addition, the two phases distinguish themselves in the macro structure. Qualitative changes in the spatiotemporal ordering of a system index the establishment of new dissipative structures, while the emergence of a limit-cycle oscillation marks the signature of a stabilized thermodynamic engine. The analysis of the maintenance phase constitutes the chief concern of homeokinetic physics.

Homeokinetics views any relative constancy in biological systems as an emergent and distributed property (a steady-state operating point) of a thermodynamic engine complex. Thermodynamic engines constitute energy-flow systems that draw from a high potential source, reject some to a lower potential sink and do work in a periodic limit-cycle fashion. The amplitude and period of oscillations are determined by the geometric layout of the source–sink, energy-flow system, independent of initial conditions. The limit-cycle periodicity indexes the important energy transactions going on within a thermodynamic system, and the time domains in which it occurs. The limit-cycle, then, is the characteristic signature of an autonomous thermodynamic engine.

The conclusion to be drawn from the theories of Dissipative Structures and Homeokinetics is that there is an inherent possibility for the creation and maintenance of qualitatively new spatiotemporal orderings in thermodynamically-open systems when specific nonlinear interactions are realized. From a more general viewpoint, the principles of nonequilibrium thermodynamics provide a unified framework, as well as an appropriate language for analyzing complex and diverse phenomena in living systems. The core thesis of such an analysis is that the flow of energy and matter through a system, in the nonequilibrium thermodynamic sense, acts to organize and maintain that system. (See p. 43 for a list of general requirements for this organizing principle to manifest itself.)

6.1.2 A Commitment to the Tenets of Ecological Realism

The ecological approach to perception and action incorporates psychology as a companion endeavor to physics and biology for the purpose of studying the epistemological relationship between an animal, as agent and perceiver, and its environment. The goal of a theory of action and perception is to explicate the organizational principles relating animal and environment on the basis of energy and informational transactions. A commitment to ecological realism starts with the assumptions of (i) a mutuality or synergy of animal and environment as an ecosystem and (ii) information as unique and specific to the dynamics of that ecosystem. Specifically, the ecological perspective denies the legitimacy of approaches that separate animal and environment such that a new and special third class of terms (e.g. set-points, programs, schemas, etc.) must be introduced to mediate the control and co-ordination between them. In addition, the ecological approach denies the introduction of a semantically neutral set of information descriptors (e.g. bits). The concept of information mandated by the ecological approach necessitates that information be defined as *unique*, *specific* and *meaningful* to the control and co-ordination requirements of activity. Moreover, as we have sought to show in the present chapter, information must be *continuously scaled to the dimensions of the system* over which the activity is defined.

The confluence of the two themes of (1) energy flow as a self-organizing and self-maintaining principle and (2) information as unique and specific to activity may be found in the morphology of a biological system's dynamics. The particular order exhibited by a thermodynamic system depends in a very detailed way on the geometric properties that define the source–sink, energy-flow system. Geometric properties are continuously scaled to the dimensions of the thermodynamic system and unique and specific to its stable and dissipative properties.

6.1.3 Information as Form: The Establishment of an Intrinsic Metric

> ... any geometric form whatsoever can be the carrier of information, and in the set of geometric forms carrying information of the same type the topological complexity of the form is the quantitative scalar of the information.
>
> Thom (1975, p. 145)

The concept of information as form has primary application to a class of 'well-organized' functions whose variables may be decomposed into the subdivisions of non-essential and essential. Following Gel'fand and Tsetlin nonessential variables bring about marked changes in the value of the function but leave the topological qualities of the function unaltered, and essential variables determine the function's topological qualities. An important aspect of such functions is that the particular characteristics of the organization need not be known in advance. Transformations over the function are sufficient to reveal the intrinsic properties. When this class of functions is defined over a dynamic system, the qualitative properties of the functions are revealed in the forms of dramatic gradients and equilibrium points. While the division into essential and non-essential may not be possible for all mathematical functions, many of the functions (probably the majority) of living systems capture this decomposition. In formulating the mathematical theory of nonlinear differential equations Poincaré provided the first formal analysis of well-organized functions in dynamic systems. Using the powerful tools of qualitative analytic-topology Poincaré was able to provide a classification of stable temporal periodicities in nonlinear systems. More recently, Thom's somewhat general formulation of morphogenesis in terms of the topological theory of ordinary differential equations has provided a broad classification of situations arising at the bifurcation points or, to use Thom's terminology, at the catastrophe points.

The issue of 'well-organized' functions bears directly on the problems of self-organization and self-maintenance in physical systems. Prior to the establishment of a stable spatiotemporal ordering, the system is at equilibrium and behaves in a linear way. Under sufficient scale changes however, the system shifts from a linear to a nonlinear mode of behavior. Scale changes then create an instability in the system, driving it to a new stable spatiotemporal structure. In the new organization linear and nonlinear variables evolve an organization allowing for the possibility of the creation and maintenance of new stable orderings. This organizational strategy offers a degree of flexibility and precision in the behavior of the system by virtue of the *form* of its linear properties, and a degree of stability in the system's behavior due to the *form* of its nonlinear variables. In short, the organization reveals a functional basis for *control* (precision and flexibility) and *co-ordination* (stability) in the *forms* (as information) of the linear and nonlinear components respectively. (For more details on the concepts of control and co-ordination in terms of functional forms see Kugler, Kelso, and Turvey, 1980.)

In conclusion, in this chapter we have attempted to provide a unified theoretical framework which stands accountable to the developmental problems associated with scale and dimensional changes. A unique aspect of this formulation is its attempt to undercut the classical separation between the high power, energy converting machinery (corresponding to the dynamical aspects of the system) and the low power, communicational signals (corresponding to the linguistic component of the system). In wedding contemporary physical theory to the ecological theory of perception and action, we have taken a first step toward establishing an intrinsic metric for the concept of information. According to this view, information is a *physical* variable that is unique and specific to the changing geometry of a system's dynamics. We suspect rather strongly that only this notion of information places satisfactory and nonarbitrary restrictions on the solution to the degrees of freedom problem in naturally developing systems. That is, without an intrinsic metric for information, we see little chance of an adequate rationale emerging for how movements are co-ordinated and controlled in a system whose dimensions change in magnitude gradually (as in growth) or artificially (as when an organism performs instrumental activity).

ACKNOWLEDGMENTS

The writing of this chapter was supported by NIH Grants NS 13617, AM 25814 and HD 01994 and Biomedical Research Support Grant RR 05596 to Haskins Laboratories. We are indebted to Arthur Iberall for reviewing an earlier version and Claudia Carello for making the figures.

NOTE

1. Prigogine has termed the new regime a dissipative structure to emphasize the entropy-producing field processes inside the system which serve to create and maintain the order. Iberall, on the other hand, regards this as the near equilibrium thermodynamic processes – including chemical change – which have been studied by hydrodynamicists since Maxwell, Reynolds, Rayleigh, Helmholtz, Kirchoff, etc. The nonequilibrium of chemistry is only a near equilibrium in thermodynamics. According to the homeokinetic school, what requires novelty of treatment is how to introduce the 'symmetry breaking' of matter condensation.

REFERENCES

Adams, J. A. (1971). A closed-loop theory of motor learning, *Journal of Motor Behavior*, **3**, 111–150.

Alexander, R. M. (1968). *Animal Mechanics*, University of Washington Press.

Apter, M. J. (1966). *Cybernetics and Development*, London: Pergamon Press.

Attneave, F. (1959). *Applications of Information Theory to Psychology: A summary of basic concepts, methods and results*, New York: Holt.

Baerends, G. P. (1976). The functional organization of behavior, *Animal Behavior*, **24**, 726–738.

Balescu, R. (1975). *Equilibrium and Nonequilibrium Statistical Mechanics*, New York: Wiley.

Bayley, N. (1933). Development of motor abilities during the first three years, *Monograph Society of the Research in Child Development*, **1**.

Bellman, R. E. (1961). *Adaptive Control Processes*, Princeton, NJ: Princeton University Press.

Berlinski, D. (1976). *On Systems*, Boston: MIT Press.

Bernard, C. (1949). *An Introduction to the Study of Experimental Medicine*, New York: Schuman.

Bernstein, N. (1967). *The Coordination and Regulation of Movements*, London: Pergamon Press.

Bertalanffy, L. von. (1973). *General System Theory*, Harmondsworth, England: Penguin.

Bloch, E. and Iberall, A. (1974). The functional unit of mammalian skeletal muscle, *Anatomical Record*, **178**, 312.

Bohm, D. (1957). *Causality and Chance in Modern Physics*, London: Routledge and Kegan Paul.

Bridgeman, P. W. (1922). *Dimensional Analysis*, New Haven, CT: Yale University Press.

Bridgeman, P. W. (1941). *The Nature of Thermodynamics*, Cambridge, Mass.: Harvard University Press.

Brookhart, J. M., and Stein, P. S. G. (1980). *Locomotion*, Quincy, Mass.: Grass Instrument Co.

Bunge, M. (1977). Levels and reductions, *American Journal of Physiology*, **233**, R75–R82.

Cannon, W. (1939). *The Wisdom of the Body*, New York: Norton.

Chapman, S., and Cowling, T. (1952). *The Mathematical Theory of Non-uniform Gases*, Cambridge, England: Cambridge Univ. Press.

Connolly, K. (1970). *Mechanisms of Skill Development*, New York: Academic Press.
Cornman, J. W. (1975). *Perception, Common Sense, and Science*, New Haven: Yale Univ. Press.
DeGroot, S. R., and Mazur, P. (1962). *Non-equilibrium Thermodynamics*, Amsterdam: North-Holland.
Dewey, J., and Bentley, A. F. (1949). *Knowing and the Known*, Boston: Beacon.
Elsasser, W. M. (1958). *The Physical Foundation of Biology*, Oxford: Pergamon Press.
Fitch, H., and Turvey, M. T. (1978). On the control of activity: Some remarks from an ecological point of view, in R. Christina (ed.), *Psychology of Motor Behavior and Sports*, Urbana, Ill.: Human Kinetics.
Fodor, J. A. (1975). *The Language of Thought*, New York: Thomas Y. Crowell.
Fowler, C., Rubin, P., Remez, R., and Turvey, M. T. (1980). Implications for speech production of a general theory of action, in B. Butterworth (ed.), *Language Production*, London: Academic Press.
Fowler, C. A., and Turvey, M. T. (1978). Skill acquisition: An event approach with special reference to searching for the optimum of a function of several variables, in G. Stelmach (ed.), *Information Processing in Motor Control and Learning*, New York: Academic Press.
Gelfand, I. M., Gurfinkel, V. S., Tsetlin, M. L., and Shik, M. L. (1971). Some problems in the analysis of movements, in I. M. Gelfand *et al.* (eds.), *Models of the Structural-functional Organization of Certain Biological Systems*, Cambridge: MIT Press.
Gelfand, I. M., and Tsetlin, M. L. (1962). Some methods of control for complex systems, *Russian Mathematical Surveys*, **17**, 95–116.
Gibson, J. J. (1950). *The Perception of the Visual World*, Boston: Houghton Mifflin.
Gibson, J. J. (1966). *The Senses Considered as Perceptual Systems*, Boston: Houghton Mifflin.
Gibson, J. J. (1979). *The Ecological Approach to Visual Perceptions*, Boston: Houghton Mifflin.
Glansdorff, P., and Prigogine, I. (1971). *Thermodynamic Theory of Structure, Stability and Fluctuations*, New York: Wiley-Interscience.
Greene, P. H. (1972). Problems of organization of motor systems, in R. Rosen and F. Snell (eds.), *Progress in Theoretical Biology* (Vol. 2), New York: Academic Press.
Gregory, R. L. (1974). *Concepts and Mechanisms of Perception*, New York: Scribner.
Grillner, S. (1975). Locomotion in vertebrates. Central mechanisms and reflex interaction, *Physiological Review*, **55**, 247–304.
Haken, H. (1977). *Synergetics*, Heidelberg: Springer-Verlag.
Halverson, L. E., and Roberton, M. A. (1966). A study of motor pattern development in young children, *Abstracts*, Research Section, National Convention, American Association for Health, Physical Education and Recreation.
Halverson, L. E., Roberton, M. A., and Harper, C. J. (1973). Current research in motor development, *Journal of Research and Development in Education*, **6**, 56–70.
Hanson, N. R. (1974). *Patterns of discovery*, Cambridge: Cambridge University Press.
Helmholtz, H. von (1925). In J. P. Southall (ed. and trans.), *Treatise on Psychological Optics*, Rochester, NY: Optical Society of America.
Hertel, H. (1966). *Structure, Form, Movement*, New York: Reinhold.
Holst, F. von (1973). *The Behavioral Physiology of Animals and Man*, Coral Gables, Fla.: University of Miami Press.
Iberall, A. (1969). New thoughts in biocontrol, in C. Waddington (ed.), *Towards a Theoretical Biology* (Vol. 2), Edinburgh: Edinburgh University Press, pp. 166–178.

Iberall, A. S. (1972). *Toward a General Science of Viable Systems*, New York: McGraw-Hill.

Iberall, A. S. (1975). On nature, man and society: A basis for scientific modeling, *Annals of Biomedical Engineering*, **3**, 344–385.

Iberall, A. S. (1977). A field and circuit thermodynamics for integrative physiology: I. Introduction to general notions, *American Journal of Physiology/Regulatory, Integrative, & Comparative Physiology*, **2**, R171–R180.

Iberall, A. S. (1978a). Cybernetics offers a (hydrodynamic) thermodynamic view of brain activities. An alternative to reflexology, in F. Brambilla, P. K. Bridges, E. Endroczi and C. Heusep (eds.), *Perspectives in Endocrine Psychobiology*, New York: Wiley.

Iberall, A. S. (1978b). A field and circuit thermodynamics for integrative physiology: III. Keeping the books – a general experimental method, *American Journal of Physiology/Regulatory, Integrative, & Comparative Physiology*, **3**, R85–R97.

Iberall, A., and McCulloch, W. S. (1970). Homeokinesis – the organization of complex living systems, in A. S. Iberall and J. B. Reswick (eds.), *Technical and Biological Processes of Control: A cybernetic view*, Pittsburgh, Penn.: Instrument Society of America.

Iberall, A. S., and Soodak, H. (1978). Physical basis for complex systems – some propositions relating levels of organization, *Collective Phenomena*, **3**, 9–24.

Iberall, A. S., Soodak, H., and Arensberg, C. (in press). Homeokinetic physics of societies – a new discipline – autonomous groups, cultures, politics, in H. Reul, D. Ghista, and G. Rau (eds.), *Perspectives in Biomechanics*, New York: Harwood Acad.

Iberall, A. S., Soodak, H., and Hassler, F. (1978). A field and circuit thermodynamics for integrative physiology. II. Power communicational spectroscopy in biology, *American Journal of Physiology*, **3**, R3–R19.

Jammer, M. (1974). *The Philosophy of Quantum Mechanics: The interpretations of quantum mechanics in historical perspective*, New York: Wiley-Interscience.

Johnston, T. D., and Turvey, M. T. (1980). An ecological metatheory for theories of learning, in G. H. Bower (ed.), *The Psychology of Learning and Motivation*, New York: Academic Press, pp. 147–205.

Keele, S. W. (1980). A behavioral analysis of motor control, in V. Brooks (ed.), *Handbook of Physiology: Motor control*, Washington DC: American Psychological Society.

Keele, S. W., and Summers, J. (1976). The structure of motor programs, in G. E. Stelmach (ed.), *Motor Control: Issues and trends* New York: Academic Press, pp. 109–142.

Kelso, J. A. S. (1981). Contrasting perspectives on order and regulation in move-of coordinative structures as dissipative structures: II. Empirical lines of con-NJ: Lawrence Erlbaum.

Kelso, J. A. S., Holt, K. G., Kugler, P. N., and Turvey, M. T. (1980). On the concept of coordinative structures in dissipative structures: II. Empirical lines of convergence, in G. E. Stelmach and J. Requin (eds.), *Tutorials in Motor Behavior*, New York: North-Holland.

Kohler, W. (1969). *The Task of Gestalt Psychology*, Princeton, NJ: Princeton University Press.

Koschmeider, E. L. (1975). Stability of supercritical Bénard convection and Taylor vortex flow, in I. Prigogine and S. A. Rice (eds.), *Advances in Chemical Physics*, New York: Wiley.

Koschmeider, E. L. (1977). Instabilities in fluid dynamics, in H. Haken (ed.), *Synergetics*: A workshop, New York: Springer-Verlag.

Kugler, P. N., and Turvey, M. T. (1979). Two metaphors for neural afference and efference, *The Behavioral and Brain Sciences*, **2**.

Kugler, P. N. K., Kelso, J. A. S., and Turvey, M. T. (1980). On the concept of co-ordinative structures as dissipative structures: I. Theoretical lines of convergence, in G. E. Stelmach and J. Requin (eds.), *Tutorials in Motor Behavior*, New York: North-Holland, pp. 1–47.

Lee, D. H. (1976). A theory of visual control of braking based on information about time-to-collision, *Perception*, **5**, 437–459.

MacKay, D. M. (1969). *Information, Mechanism, and Meaning*, Cambridge, Mass.: MIT Press.

Mandle, C. (1971). *Perception: Facts and Theories*. Oxford: Oxford Univ. Press.

McGraw, M. B. (1941). Development of neuro-muscular mechanisms as reflected in the crawling and creeping behavior of the human infant, *Journal of Genetic Psychology*, **58**, 83–111.

McGraw, M. B. (1945). *The Neuro-Muscular Maturation of the Human Infant*, New York: Columbia University Press.

Minsky, M., and Papert, S. (1972). Artificial intelligence, *Artificial Intelligence Memo, 252*, Cambridge, Mass.: Artificial Intelligence Laboratory, MIT.

Mitchell, D., Snellen, J. W., and Atkins, J. R. (1970). Thermoregulation during fever: Change in setpoint or change in gain, *Pflugers Archives*, **321**, 293.

Morowitz, H. J. (1968). *Energy Flow in Biology; Biological organization as a problem in Thermal Physics*, New York: Academic Press.

Morowitz, H. J. (1978). *Foundations of Bioenergetics*, New York: Academic Press.

Mundle, C. W. K. (1971). *Perception: Facts and theories*, London: Oxford University Press.

Nazarea, A. D. (1974). Critical length of the transport-dominated region for oscillating non-linear reactive processes, *Proceedings of the National Academy of Science* (USA), **71**, 3751–3753.

Nicolis, G., and Prigogine, I. (1971). Fluctuations in nonequilibrium systems, *Proceedings of the National Academy of Science* (USA), **68**, 2102–2107.

Nicolis, G., and Auchmuty, J. F. G. (1974). Dissipative structures, catastrophes, and pattern formation: a bifurcation analysis, *Proceedings of the National Academy of Science* (USA), **71**, 2748–2751.

Nicolis, G., and Prigogine, I. (1977). *Self-organization in Nonequilibrium Systems: From dissipative structures to order through fluctuations*, New York: Wiley-Interscience.

Nicolis, G., Prigogine, I., and Glansdorff, P. (1975). On the mechanism of instabilities in nonlinear systems, in I. Prigogine and S. Rice (eds.), *Proceedings of the Conference on Instability and Dissipative Structures in Hydrodynamics*, New York: Wiley-Interscience.

Onsager, L. (1931). Reciprocal relations in irreversible processes, *Physiological Reviews*, **37**, 405.

Pattee, H. H. (1972a). Physical problems of decision-making constraints, *International Journal of Neuroscience*, **3**, 99–106.

Pattee, H. H. (1972b). Laws and constraints, symbols and language, in C. H. Waddington (ed.), *Towards a Theoretical Biology*, Chicago: Aldine.

Pattee, H. H. (1973). Physical problems of the origin of natural controls, in A. Locker (ed.), *Biogenesis, Evolution, Homeostasis*, Heidelberg: Springer-Verlag, pp. 41–49.

Pattee, H. H. (1977). Dynamic and linguistic modes of complex systems, *International Journal of General Systems*, **3**, 259–266.

Pearson, K. (1976). The control of walking, *Scientific American*, 72–86.

Pew, R. W. (1974). Human perceptual motor-performance, in B. H. Kantowitz (ed.), *Human Information Processing: Tutorials in performance and cognition*, New York: Lawrence Erlbaum.

Powers, W. T. (1973). *Behavior: The control of perception*, Chicago: Aldine.

Powers, W. T. (1978). Quantitative analysis of purposive systems: Some spadework at the foundations of scientific psychology, *Psychological Review*.

Prigogine, I. (1947). *Etude thermodynamique des processus irreversibles*, Desoer, Liege.

Prigogine, I. (1967). *Introduction to Thermodynamics of Irreversible Processes* (3rd edn.) New York: Wiley-Interscience.

Prigogine, I. (1969). Structure, dissipation, and life, in M. Marois (ed.), *Theoretical Physics and Biology*, Amsterdam: North-Holland, pp. 23–52.

Prigogine, I. (1976). Order through fluctuation: self-organization and social systems, in E. Jantsch and C. H. Waddington (eds.), *Evolution and Consciousness: Human systems in transition*, Reading, Mass.: Addison-Wesley.

Prigogine, I. (1978). Time, structure, and fluctuations, *Science*, **201**, 4358.

Prigogine. I., and Nicolis, G. (1971). Biological order, structure and instabilities, *Quarterly Reviews of Biophysics*, **4**, 107–148.

Prigogine, I., and Nicolis, G. (1973). Fluctuations and the mechanism of instabilities, in M. Marois (ed.), *Proceedings of the 3rd International Conference From Theoretical Physics to Biology*, Basel: S. Karger, pp. 89–109.

Prigogine, I., Nicolis, G., and Babloyantz, A. (1972). Thermodynamics of evolution, *Physics Today*, **25**, 11–12.

Prigogine, I., Allen, P., and Herman, R. (1977). The evolution of complexity and the laws of nature, in E. Laszlo and J. Bierman (eds.), *Goals in a Global Community* (Vol. 1), Club of Rowe.

Prigogine, I., Nicolis, G., Herman, R., and Lam, T. (1975). Stability, fluctuations and complexity, *Collective Phenomena*, **2**, 103–109.

Pylyshyn, Z. W. (1980). Computation and cognition: Issues in the foundations of cognitive science, *The Behavioral and Brain Sciences*, **3**, 111–169.

Rashevsky, N. (1938/1950). *Mathematical Biophysics: Mathematical foundations of biology*, New York: Dover Publications.

Raven, C. P. (1961). *Oogenesis: the storage of development information*, London: Pergamon Press.

Riggs, D. S. (1970). *The Mathematical Approach to Physiological Problems: a critical primer*, Cambridge, Mass.: MIT Press.

Roberton, M. A. (1978). Stages in movement development, in M. Ridenour (ed.), *Motor Development: Issues and applications*, Princeton, NJ: Princeton Book Co.

Rock. I. (1975). *An Introduction to Perception*, New York: Macmillan.

Rosen, R. (1973). On the generation of metabolic novelties in evolution. In A. Locker (ed.), *Biogenesis, Evolution, Homeostasis*, Heidelberg: Springer-Verlag.

Rosen. R. (1978). *Fundamentals of Measurement and Representation of Natural Systems*, New York: North-Holland.

Runeson, S. (1977). On the possibility of 'smart' perceptual mechanisms, *Scandinavian Journal of Psychology*, **18**, 172–179.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning, *Psychological Review*, **82**, 225–260.

Shannon, C. E., and Weaver, W. (1949). *The Mathematical Theory of Communication*, Urbana: University of Illinois Press.

Shaw, R. E., and McIntyre, M. (1974). Algoristic foundations to cognitive psychology, in W. Weimer and D. Palermo (eds.), *Cognition and the Symbolic Processes*, Hillsdale, NJ: Lawrence Erlbaum.

Shaw, R., and Turvey, M. T. (1981). Coalitions as models for ecosystems: A realist's perspective on perceptual organization, in M. Kubouy and J. Pomerantz (eds.), *Perceptual Organization*, Hillsdale, NJ: Lawrence Erlbaum.

Shaw, R. E., Turvey, M. T., and Mace, W. (in press). Ecological psychology: The consequences of a commitment to realism, in W. Weimer and D. Palmero (eds.), *Cognition and the Symbolic Processes* (II), Hillsdale, NJ: Lawrence Erlbaum.

Shik, M. L., and Orlovskii, G. N. (1965). Co-ordination of the limbs during running of the dog, *Biophysics*, **10**, 1148–1159.

Soodak, H., and Iberall, A. S. (1978). Homeokinetics: A physical science for complex systems, *Science*, **201**, 579–582.

Stahl, W. R. (1962). Dimensional analysis in mathematical biology, *Bulletin of Mathematical Biophysics*, **24**, 81–108.

Thom, R. (1970). Topological models in biology, in C. H. Waddington (ed.), *Towards a Theoretical Biology* (3), Chicago, Ill.: Aldine.

Thom, R. (1975). In D. H. Fowler (trans.), *Structural Stability and Morphogenesis*, Reading, Mass.: Benjamin.

Thompson, D. W. (1917/1942). *On Growth and Form*, London: Cambridge University Press.

Tolman, R. (1938). *The Principles of Statistical Mechanics*, London: Oxford Univ. Press.

Tomović, R. (1978). Some central conditions for self-organization – what the control theorist can learn from biology, *American Journal of Physiology: Regulatory, Integrative, & Comparative Physiology*, **3**, R205–R209.

Troland, L. T. (1929). *The Principles of Psychophysiology*, New York: Van Nostrand.

Tsetlin, M. L. (1973). *Automata Theory and Modeling in Biological Systems*, New York: Academic Press.

Turvey, M. T. (1977). Preliminaries to a theory of action with reference to vision, in R. Shaw and J. Bransford (eds.), *Perceiving, Acting and Knowing: Towards an ecological psychology*, Hillsdale, NJ: Lawrence Erlbaum.

Turvey, M. T. (1980). Clues from the organization of motor systems. In U. Bellugi and M. Studdert-Kennedy (eds.), *Signed and Spoken Language: Biological constraints on Linguistic Form*, Dahlem Konferenzen, Weinheim: Verlag Chemie.

Turvey, M. T., Fitch, H. L., and Tuller, B. (in press) The problems of degrees of freedom and context-conditioned variability, in J. A. S. Kelso (ed.), *Human Motor Behavior: An Introduction*, Hillsdale, NJ: Lawrence Erlbaum.

Turvey, M. T., and Shaw, R. E. (1979). The primacy of perceiving: An ecological reformulation of perception for understanding memory, in L-G. Nilsson (ed.), *Perspectives on Memory Research: Essays in honor of Uppsala University's 500th anniversary*, Hillsdale, NJ: Lawrence Erlbaum.

Turvey, M. T., Shaw, R. E., and Mace, W. (1978). Issues in a theory of action: degrees of freedom, coordinative structures and coalitions. In J. Requin (ed.), *Attention and performance VII*, Hillsdale, NJ: Lawrence Erlbaum.

Waddington, C. H. (1969). The basic ideas of biology, in C. H. Waddington (ed.), *Towards a Theoretical Biology*, Chicago: Aldine, pp. 1–32.

Waddington, C. H. (1970). Concepts and theories of growth, development, differentiation, and morphogenesis, in C. H. Waddington (ed.), *Towards a Theoretical Biology*, Chicago: Aldine, p. 177.

Wells, K. F. (1976). *Kinesiology: Scientific Basis of Human Motion*, Philadelphia: W. B. Saunders.

Werner, J. (1977). Mathematical treatment of structure and function of the human thermoregulatory system, *Biological Cybernetics*, **25**, 93–101.

Yates, F. E. (in press). Physical biology: A basis for modeling living systems, *Journal of Cybernetics and Information Sciences*.

Yates, F. (in press). Temporal organization of metabolic processes: A biospectroscopic approach, in R. Bergman and C. Cobell (eds.), *Carbohydrate Metabolism; Quantitative physiology and mathematical modeling*, New York: Wiley.

Yates, F. E., and Iberall, A. S. (1973). Temporal and hierarchical organization in biosystems, in J. Urquhart and F. E. Yates (eds.), *Temporal Aspects of Therapeutics*, New York: Plenum.

Yates, F. E., Marsh, D. J., and Iberall, A. S. (1972). Integration of the whole organism: A foundation for a theoretical biology, in J. A. Behnke (ed.), *Challenging Biological Problems: Directions towards their solutions*, New York: Oxford University Press.

Zavalishin, N. V., and Tenenbaum, L. A. (1968). Control processes in the respiratory system, *Automation and Remote Control*, **9**, 1456–1470.