

## Inquiry into intentional systems I: Issues in ecological physics

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**Summary.** The role of intention in guiding the behavior of goal-directed systems is a problem that continues to challenge behavioral science. While it is generally agreed that intentional systems must be consistent with the laws of physics, there are many obvious differences between inanimate, physical systems and sentient, intentional systems. This suggests that there must be constraints over and above those of physics that govern goal-directed behavior. In this paper it is suggested that generic properties of self-organizing mechanisms may play a central role in the origin and evolution of intentional constraints. The properties of self-organizing systems are first introduced in the context of simple physical systems and then extended to a complex (biological) system. Whereas behavior of an inanimate physical system is lawfully determined by force fields, behavior of an animate biological system is lawfully specified by information fields. Biological systems are distinguished from simple physical systems in terms of their ubiquitous use of information fields as special (biological and psychological, social, etc.) boundary conditions on classical laws. Unlike classical constraints (boundary conditions), informational constraints can vary with time and state of the system. Because of the nonstationarity of the boundary conditions, the dynamic of the system can follow a complex trajectory that is organized by a set of spatially and temporally distributed equilibrium points or regions. It is suggested that this equilibrium set and the laws that govern its transformation define a minimal requirement for an intentional system. One of the benefits of such an approach is that it suggests a realist account for the origin of semantic predicates, thereby providing a basis for the development of a theory of symbolic dynamics. Therefore, the principles of self-organization provide a comprehensive basis for investigating intentional systems by suggesting how it is that intentions arise, and by providing a lawful basis for intentional behavior that reveals how organisms become and remain lawfully informed in the pursuit of their goals.

In general, physics seeks to understand how things change. Mechanics, a branch of physics, seeks specifically to understand inanimate motions. Biomechanics, a branch of kinesiology, seeks to understand animate motions, or movements. Our aim as psychologists is to understand how goals and/or intentions influence animate motions – a problem for ecological mechanics, or, more generally, for intentional dynamics (Shaw, Kugler, & Kinsella-Shaw, 1990; Kugler & Shaw, 1990). Traditionally, this problem has been located in the field of philosophy; later, in the collective discipline of cybernetics and control theory; and still more recently, in the field of artificial intelligence and robotics. Motivational and cognitive psychology have each perennially addressed certain aspects of the problem without appreciably reducing its problematic core. In spite of the generous efforts of all these disciplines, the role of intention in guiding self-motivated systems still remains shrouded in mystery.

The purpose of this paper is to consider some of the physical and modeling prerequisites for intentional dynamics. Of particular importance is the concept of information and its role in organizing and sustaining intentional demands. In all likelihood, the content of the problem of intentional dynamics will not be exhausted by known physical laws and their initializing conditions. However, by building upon the basis provided by classical mechanics, we hope to suggest a lawful approach to intentional behavior that follows from, and is consistent with, the constraints put forth by physical theory. In this way, an account of intentional behavior would be viewed as a natural extension of, but not logically reducible to, theories describing the motion of inanimate objects.

### Generic conditions that create and annihilate equilibrium points

In classical mechanics, biomechanics, or ecological mechanics, the behavior of a system under observation can be plotted as a trajectory in a state space. The state of the system is defined by a set of numbers such that the know-

## POTENTIAL FIELDS

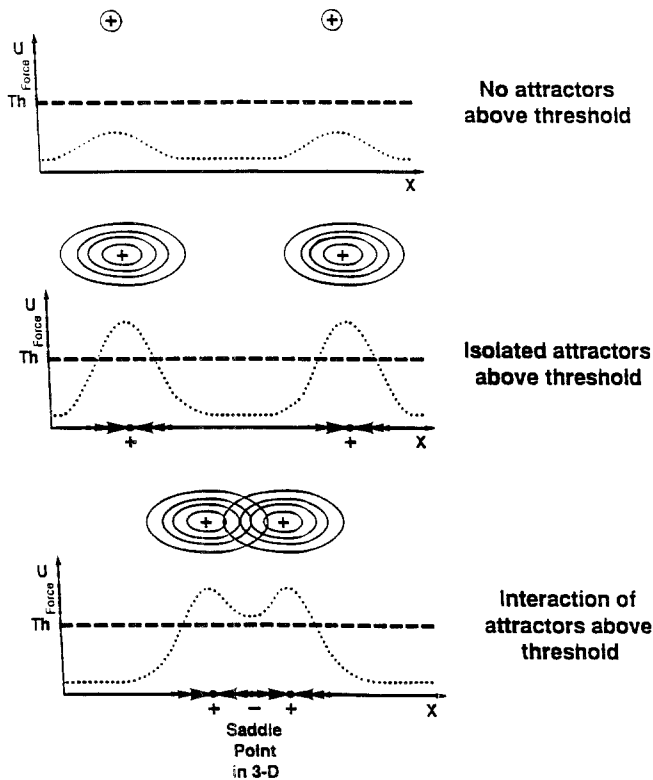


Fig. 1. Topological characteristics of magnetic gradient fields.

ledge of these numbers and the input functions will, along with equations describing its dynamics, provide the future state and output of the system. State space is therefore the set of all states reachable by the system, together with the paths to them, or alternatively, a time series defined over phase planes. In this context, the state of a system is defined as the minimum set of variables that uniquely describes the behavior of the system for any time. An obvious question that arises in trying to understand how a system changes is: What state(s) is it changing to? More specifically, in what areas of the state space do various trajectories come to rest, as time tends towards infinity? These resting states are referred to as equilibrium points. In some systems, equilibrium behavior can be characterized, not as a point, but as a cycle or as an area of the state space. An example would be a self-sustained, dissipative pendulum that is oriented by a time-dependent equilibrium region in phase space (i.e., a limit cycle region or chaotic system).

In a mathematical system, the area of the state space toward which the system converges as time tends toward infinity (whether it be a limit point, a limit cycle, quasiperiodic, or chaotic) is generically called an attractor. In a physical system, an attractor is a region of state space where the resultant force vector converges to zero. A physical system can have one or more attractors, and it is the number and layout of these attractors that influence the behavior of the system. In the case of inanimate particles, each attractor exerts a force (by means of a potential difference) on the system, and the trajectory that the system

follows is determined by the net sum of the forces exerted by the various attractors. In this sense, the temporal flow of events in a dynamic system can be said to be organized by its attractors.

As examples of attractors, one might think of the poles of a magnet for an oppositely charged particle, a drain in a sink where water runs downhill because of gravity, or of the food toward which a hungry animal moves. In the strictly physical cases the attractor is a minimum of a global field (e.g., magnetic and gravitational, respectively). In the psychological case, a goal toward which an animal directs its movements (such as food for a hungry animal) is a different sort of attractor – but an attractor no less. To appreciate the attractor dynamics for goal-directed behaviors will require that we extend classical field theory. Before we can extend it, however, we must understand its limitations. We turn to this topic next before returning to the role of attractors in expressing intentions – what we have called intentional dynamics (Shaw et al., 1990; Kugler & Shaw, 1990).

### Competing attractors

The familiar context of a magnetic field can help to illustrate the influence of attractors on the behavior of a system. Consider the magnetic field produced by two positively charged magnets that are in fixed locations along a flat surface. The magnets are under a flat rigid sheet that is permeable to the magnetic field. A negatively charged particle placed on the top surface will be oriented by the positively charged magnets; that is, the magnets define attractors for a negatively charged particle. The particle's motion is also influenced by the contact friction coupling the particles to the flat surface. This friction defines a force threshold below which there is no motion of the particle. Figure 1 provides three qualitatively different cases of such an arrangement.

The threshold on each of the cross-section graphs represents the minimum amount of force required to move the negatively charged particle (i.e., the amount of force required to overcome friction). For each of the three cases, a horizontal cross-section of the magnetic field is presented. The cross-sections reveal only the portion of the magnetic field that is above the frictional threshold. This portion defines the force contribution that scales to the motion of the particle in the field.

Figure 1a illustrates the case where the peak values of the force field surrounding both of the magnets are too weak to have any effect on the particle. So, from the perspective of the negatively charged particle, there is no substantial force field. Figure 1b describes what happens when two stronger magnets are placed in the same two locations. Now, the force field exceeds the threshold in certain regions. Thus, if the negatively charged particle is placed close enough to either magnet, it will experience an attractive force that will move it toward that magnet. In this situation, each magnet serves as an attractor, or equilibrium point, for the negatively charged particle. However, if the particle is placed somewhere near the mid-point between the two attractors, it will remain there, since the force fields

in this location are not strong enough to move the particle. In the configuration shown in Figure 1b, then, there are two independent attractors in different areas of the field. There is no interaction between the two, and therefore no competition. Depending on where the particle is, either it experiences the attractive force of one of the attractors, or it experiences no significant force at all.

Finally, in Figure 1c, the two strong magnets used in the previous case are brought closer together. This results in a qualitatively different type of situation, since the force fields of the two magnets interact in the region between them. As in the previous case, there are still two attractors, but now there is also a competition between the attractors. If placed in certain regions, the negatively charged particle will feel the force of both attractors. As we shall see later on, this will result in nonlinear behavior. Basically, a very slight shift in the initial location of the particle in the region of the "valley" separating the two force fields may make it move toward one attractor rather than the other.

The point of this example is to show how the configuration of attractors has a critical influence on the behavior exhibited by a dynamic system. A change in the attractor layout will result in a qualitative shift to a different behavior mode. In the above example, three different modes (no motion, linear motion to a single attractor, and nonlinear motion resulting from a competition between attractors) were illustrated, corresponding to three different attractor layouts (subthreshold force fields, independent force fields, and interacting force fields). The limitation of this example is that the location of the attractors was fixed beforehand by the placement of the magnets. Thus, there is no self-organization taking place.

The remainder of this section will be concerned with the question of how attractors can be spontaneously created and annihilated, thereby resulting in self-organizing behavior. It is axiomatic to the argument we pursue that only self-organizing systems are capable of intentional dynamics (i.e., goal-directed behavior). Only systems that are open to energy, matter, and information flows can exhibit this type of behavior.

### *Maximum entropy versus self-organization*

In an isolated system (i.e., one closed to the flow of energy and matter), the temporal flow of events is organized by an attractor defined by the state of maximum entropy<sup>1</sup>. The attractive influence of this equilibrium point on an isolated system's dynamic is stated formally in the Second Law of Thermodynamics. In an isolated system, the organizational state evolves over time to a state of maximum entropy, at which time no further change will occur. As a result, the entropy of the universe will tend to a maximum value (Atkins, 1984). This implies that the intrinsic evolutionary

<sup>1</sup> Entropy is a measure of disorder, randomness, or uniformity. Any of these terms can be used interchangeably to denote the same concept. Thus the point of maximum entropy can be described as a state of: maximum disorder; complete randomness; or maximum uniformity. A decrease in entropy, therefore, is equivalent to an increase in the structure, organization, or order, in a system.

tendency of the universe is toward states of increasing disorder, ultimately converging onto a state of equilibrium where disorder is maximum. Once at equilibrium, all future possibilities of change are eliminated.

Unlike most physical systems, self-organizing systems evolve away from the state of maximum disorder (i.e., decreases in entropy). How is it possible to reconcile this with the Second Law of Thermodynamics? Does the existence of intentional systems contradict this basic law of physics? This is a question that has puzzled scientists for many years. However, recent work on self-organization suggests that movement away from maximum entropy can be achieved through the emergence of new equilibrium points that compete for control of the system's dynamic. In effect, there may be one or more attractors that, in addition to the point of maximum entropy, are simultaneously affecting the behavior of the system. If a new equilibrium point is strong enough, it can seize control of the dynamic from the influence of maximum entropy and evolve the system toward states of greater order, in local defiance of the Second Law.

The science of self-organization studies the dynamics of systems that intrinsically and autonomously create and annihilate equilibrium points. The following provides a historical introduction to the role of maximum entropy in orienting a system's behavior, as well as describing how this role changes when the system is open to external flows of energy and matter. It is upon this fact that the possibility of explaining intentional systems rests.

### *Irreversible processes, disorder, and isolated systems*

In the physical sciences, matter can be studied at several distinct scales of organization. On the small scale, a great deal is known about the internal structure of atoms, their motions, and their mutual interactions, which produce more complex entities. This corpus of knowledge constitutes a microscopic view of nature. On the large scale, a great deal is known about the properties of bulk matter, for example its electrical or magnetic properties, or the affinity of substances towards each other. Properties and relations observed on this scale form the macroscopic theories of matter. One of the laws defining observations on this scale is the Second Law of Thermodynamics. The law identifies why a drop of ink tends to spread out in a glass of water instead of remaining a localized spot. This same law also predicts that heat will always flow from hot regions to cooler regions. Because the Second Law makes predictions about evolutionary sequences in time, processes which fall under its reign are referred to as irreversible processes. Once the event unfolds in time, the reverse process becomes impossible. The system remains at the equilibrium point of maximum entropy. Thus, the ink will not spontaneously form a small drop again and a hot spot will not spontaneously appear in a cool region. But to have goals spontaneously arise as attractors for a living system demands such self-organizing tendencies.

Once at equilibrium, all possibility of change disappears and all that remains are stationary processes that preserve the order of the system constant in time. These are

referred to as reversible transformation processes. Reversible processes do not increase or decrease the entropy of a system. Once a system's process enters into a reversible mode, no change in order can develop as long as the system remains isolated. If, however, the system becomes open to the exchange of energy and matter with other systems, then it is possible that local regions within the total system can achieve a decrease on entropy over time (i.e., an increase in complexity, organization, or order). In these regions, non-stationary, irreversible processes can develop that selectively organize or mix the bulk-matter properties (temperature, pressure, chemical concentration, etc.) into states of increased order. The increase in order of local regions is made possible through the siphoning of entropy to neighboring areas, thereby resulting in an overall system whose total entropy increases with time in agreement with the Second Law. It is in these regions of nonstationary processes that open systems capable of intentional dynamics must have evolved.

#### *Irreversible processes, order, and open systems*

Classical thermodynamics was associated with the forgetting of initial conditions and the destruction of structure. We now know that, within the framework of thermodynamics, there is another set of phenomena in which structure may spontaneously appear (Prigogine, 1980). Some of the most influential early investigations into the relationship between irreversible processes and open systems were made by Prigogine and his colleagues, starting in the mid 1940s, and extending for more than three decades (e.g., Prigogine, Nicolis, & Babloyantz, 1972; Nicolis & Prigogine, 1977; Prigogine & Stengers, 1984). These investigations involved models of chemical systems in which competitions developed between the flows that couple various components of reaction mechanisms. At the time it was believed that the temporal evolution of a system's states was along a linear relaxation trajectory, that is, a trajectory that inevitably moves the system through states of increasing disorder toward a final state of maximum disorder (entropy). This trajectory follows the strictly destructive path prescribed by the Second Law of Thermodynamics in an isolated system. It was further assumed that the consequences of the Second Law were the same for both isolated and open systems.

In contrast to these traditional assumptions, Prigogine and his colleagues found that when their chemical systems were displaced far from equilibrium by the pumping of energy into the system, the linear relaxation dynamic broke down and was replaced by a nonlinear dynamic that drove the system locally further away from equilibrium. In this far-from-equilibrium region, a new thermodynamic path

(branch) formed, yielding constructive effects as a byproduct of the Second Law's dissipative processes<sup>2</sup>. The system exhibited a natural tendency toward self-organization. In recognition of the central role played by dissipative processes in self-organization, Prigogine termed these open systems *dissipative structures*.

But can these principles alone explain systems that exhibit intentional dynamics? What other modeling principles are needed? To begin this inquiry, let us first consider the structure of the reaction mechanism in a purely physical context, and then extend it to a biological context.

#### *Nonlinearity, multiple equilibrium points, and instability*

To form a consistent theory of reaction mechanisms that applies to both isolated and open systems, it is necessary to depart from the traditional strategy of modeling the evolutionary dynamics in terms of a thermodynamic state space containing only a single equilibrium point. This equilibrium point is defined by the state of maximum entropy (minimum order). As time tends towards infinity, the system continuously converges on the state of maximum entropy (under given boundary conditions) in accordance with demands from Second Law processes. To accommodate the new findings of open systems, however, it is necessary to redefine the thermodynamic constraints in a manner that allows for the emergence of multiple equilibrium points in certain regions of state space. The new equilibrium points are added to state space by the introduction of nonlinear-force terms (e.g., quadratic or higher order) into the original state equation. According to the new equation, the state of maximum entropy identifies an equilibrium point in state space that operates when the system is both closed and open to external interactions.

As the system is displaced further from the local state of maximum entropy through the addition of energy, additional equilibrium points (some stable and some unstable) begin to emerge and influence the behavior of the system. At first, the equilibrium point at the state of maximum entropy exerts the most dominant influence on the system's dynamic. As the system is displaced further from this equilibrium region, however, a separatrix is crossed where the forces exerted by the new equilibrium point(s) exceed those of the old equilibrium point and act in the opposite direction. At the separatrix region there is a competition between the two neighboring equilibrium points. In this region both equilibrium points are attempting to gain control of the system. Beyond the separatrix the new equilibrium point seizes control of the system. The influence of the new equilibrium point displaces the system further away from the state of maximum disorder (thermodynamic equilibrium). As the system evolves away from the separatrix, it moves toward a state of greater order: the system self-organizes.

A self-organizing mechanism creates and/or annihilates equilibrium points. The mechanism is composed of a coupling of two processes that generate opposing tendencies. For example, the competition can be between the tendencies of a dissipative process and the tendencies of an escapement process. If the system is dominated by the

<sup>2</sup> A dissipative process involves a loss of energy from macro to micro degrees of freedom. The prototypical example is friction. Thus, a block sliding on a table will slow down (lose energy from the macro mode), and at the same time dissipate energy in the form of heat (micro mode). According to the Second Law, as time tends towards infinity, the energy in an isolated system will dissipate from macro modes to micro modes, resulting in an increase in entropy.

dissipative process, then the local maximum entropy attractor will have the greater significance in orienting the behavior of the system. If, however, the escapement process dominates, then the behavior of the system can be driven locally away from the state of maximum entropy under the influence of a new equilibrium point.

### *A simple example and summary*

The patterns of behavior associated with self-organization can be made more concrete through a simple example. Take the case of a falling leaf (Kugler & Turvey, 1987, p. 123), illustrated in Figure 2. Most leaves dropped from sufficient height above the ground exhibit behavior in three qualitatively different modes of dynamical organization. The first of these is the translational mode, during which the leaf falls straight down. As it accelerates, however, the falling leaf absorbs more and more energy. Because of the large amount of energy being pumped into the leaf, a critical point emerges where this dynamical system is no longer stable in the translational mode. At this point, the leaf's behavior self-organizes into a new dynamical mode characterized by a side-to-side vibration. This mode consumed the excess energy pumped into the system, permitting its behavior to stabilize. However, as the leaf continues to fall, even more energy accrues, causing the leaf's behavior again to become unstable. Consequently, its behavior must self-organize into an even higher mode. In this third mode, the leaf begins to spin about itself. The example illustrates how increasing the amount of energy flowing into a system causes it to self-organize recursively into successively more complex modes of behavior in order to maintain dynamical stability. From this example, the fundamental process by which an open system self-organizes can be abstracted. Can such reorganization give rise to intentional modes of behavior? This is a question that we shall address in the next section. Before doing so, let us recall the stages of the self-organizing process.

Motion in an isolated system is governed solely by the First Law, which states that the total energy in the system (i.e., the sum of potential and kinetic energy) remains constant in a given measurement frame. As a result, the system dynamics are reversible and conservative. However, as the system is opened slightly to energy flows, the Second Law comes into play. Here the equilibrium point of maximum entropy plays the role of an attractor, irreversibly drawing the system to it. During this irreversible mode of behavior, the dissipative term dominates the system's dynamic. As more energy is added, however, the escapement term begins to dominate and sets up a reversal of forces by creating a competing attractor. This force reversal causes the system to become temporarily unstable and to lurch suddenly farther from equilibrium. In general, competition between equilibrium points (i.e., attractors) produces new nonlinearities in a system's macroscopic behavior whenever it enters regions where force reversals occur. The set of points in the region of force reversal is called a *separatrix*. The path from a separatrix to new points (or regions) of equilibrium results in the emergence of a dynamic regime with more macroscopic spatial and temporal scales. The evolution of a dynamic structure toward a more macroscopic scale is a fundamental characteristic of the thermodynamic theory of self-organization.

The process of self-organization can proceed in a recursive manner. As the system is displaced further from the new attractor a third equilibrium point can emerge and begin competing for control of the system. While the system is evolving further and further away from a microscopically defined equilibrium state, the system remains relatively close to the equilibrium state defined macroscopically (see Soodak & Iberall, 1987, for a related discussion of near equilibrium requirements). The identification and application of these critical relationships between nonlinearity, open systems, and self-organization is currently a prominent topic on the scientific agenda in the physical, biological, and social sciences. (See e.g., Casti, 1989; Carreri, 1984; Davies, 1989; Haken, 1988; Nicolis & Prigogine, 1989; Yates, 1987).

The main point of the next section is to show how nonlinear thermodynamics is not restricted to causal inanimate systems but can be generalized to intentional animate

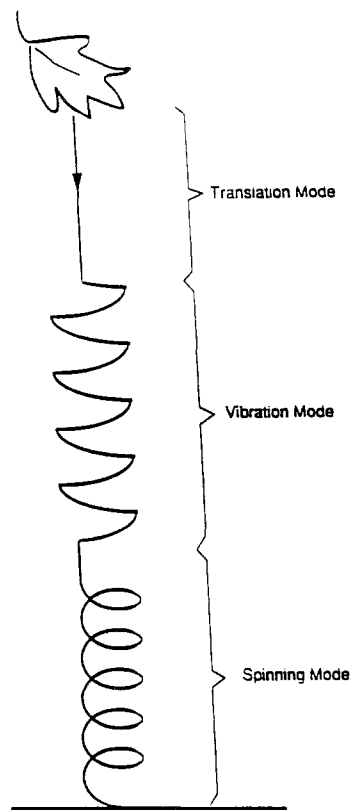


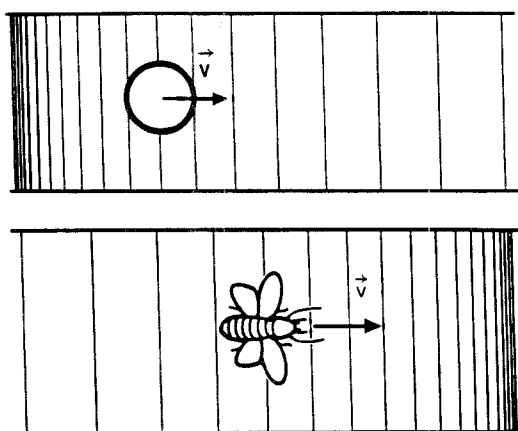
Fig. 2. Dynamic modes (translation, vibration, and spinning) of a falling leaf.

systems. Our aim is not to reduce all intentional dynamics to thermodynamics, but to show how the latter can be elaborated consistently to help account for the former. If a system is to be controlled, then, there must be energetic couplings to attractors in the state space. But this is not enough. To be intentionally controlled, there must also be informational couplings to these attractors. Later we show how information plays a role in the latter couplings not unlike forces do in the former couplings.

### *Primitive intentions, derived intentions, and other orienting remarks*

We enter the problem of intentionality by focusing primarily on the role of primitive intentions. We believe that this more modest concern provides a more realistic place to begin a theory of intentional dynamics rather than trying to deal immediately with cases of free volition. This main point is illustrated in Figure 3 and discussed in more detail in the following section. Here we see that whereas an inanimate object (e.g., a molecule) is causally restricted to move according to force gradients, an actor (e.g., an insect) is capable of being causally influenced by both force fields and information fields. As a system moves from primitive to higher-order intentions, the focus of constraints shift from the force fields to the information fields as less work is done and more information is required.

Compare the work required if one chooses not to breathe, as opposed to choosing not to speak. Now compare the information required to regulate your breathing with the information required to regulate speech. Symbol



**Fig. 3.** Upper panel: the motion of the pheromone particle is a reaction to forces generated in an external frame of reference; the internal frame of reference is isolated from the external frame. Lower panel: the motion of the insect is generated by forces that are generated in both the external and the internal frames of reference; the delivery of internally generated forces is constrained by a kinematic field defined by irreversible pheromone flows; the internal forces both cooperate and compete with the external forces in defining the resultant insect motion (adapted from Kugler & Turvey, 1987).

flows in linguistic fields follow forceless, but syntactically informed, gradients. Speech flows in respiratory fields follow, in part, elastic force gradients (breath groups determined by diaphragm muscles), but may violate them, as can be seen from consideration of the burp speech of laryngectomized patients. Finally, the flow of breath groups is completely informed by the neuromuscular activities. Intentional dynamics, say, as exhibited by symbol flows < speech flows < respiratory flows, range from least to most primitive in terms of their dependence on forceful gradients, but from most to least in terms of their dependence on information gradients.

Similar observations can be made about an actor choosing to follow a route by reading a map (least primitive, but most informed), a path by avoiding obstacles (more primitive, but less informed), or a trajectory while in free fall (most primitive, but least informed). In our opinion, these examples illustrate the need for a graded determinism – an explanatory continuum stretching from arbitrary rule-like to absolute law-like regulatory principles. Under this view, a system's intentional dynamics can, at different evolutionary stages or on different occasions or in different situations, be governed by laws that are more like rules, or by rules that are more like laws.

As pragmatic realists, we ecological psychologists abhor mind-body dualism precisely because we do not believe that any goal-directed system can carry out work-free intentions; but we abhor reductionism just as much because we do not believe that they can be explained by intention-free work either. We allow that Nature may generalize its operational principles, but believe it honors parsimony too much to violate them wantonly simply because intentions evolve. It seems more reasonable that what has evolved are mechanisms for intentional work. Such systems evolve in a dynamical workspace in which intentions coevolve. To leave intention out of this evolving

workspace is to abrogate one's responsibility for explaining goal-directed systems.

We now turn to an elaborate example of an open system that exhibits primitive intentions.

### Self-organization in social insects

The insects of interest are African termites, who periodically cooperate to build nests that stand more than 15 feet in height, weigh more than 10 tons, and persist in excess of 300 years. This feat is made even more remarkable by the fact that the termites work independently of each other. The insect's flight patterns are controlled locally by pheromone (molecular) distributions that arise from materials excreted by the insects and strewn by them around the building site, at first randomly, and then in increasingly more regular ways. The pheromone-laden excreted building material dictates the patterning of the collective insect activity which, in turn, determines the novel architectural structures that ultimately arise from this dynamically improvised plan. (For details obtained from naturalistic observation see Grasse, 1959, and Bruinsma, 1977; for a thermodynamic treatment see Deneubourge, 1977; for an informational approach see Kugler & Turvey, 1987).

#### *Attractor dynamics*

The nest-construction process involves the coordination of more than 5 million insects, and results in the recursive evolution of a set of macroscopic building modes:

*random depositing* → *pillar construction* → *arch construction* → *dome construction* → *random depositing* → ... and so on.

Each mode is characterized by a qualitatively different pattern of behavior. This pattern is specified by the unique number and layout of attractors in the pheromone field specific to each mode. Thus, a change in the qualitative structure of the pheromone field results in a change in mode.

The qualitative structure of the diffusion field can be classified by the layout of the attractors, which in this case are the local regions in the pheromone field where the gradient vanishes to zero. The region surrounding the attractor is the basin of attraction. The basin is defined by all the gradient flows that converge upon, or diverge from, the attractor. The attractor defines an invariant solution for all initial conditions started within the attractor's basin as time goes to infinity. Because of the field dynamics they impose, the ensemble of these attractors comprises a global organizing mechanism for local trajectories. Like the magnetic-field example presented earlier, the flow pattern is globally organized by the layout of attractors in the state space. If the layout remains constant under an action (i.e., a transformation) on the system, the pattern defining the flows is also stable. If an attractor is created or annihilated, however, the pattern defining the flow will become unstable (will change topologically). Instability in the flow field is a function of the creation and/or the annihilation of one

or more attractors; and can be either subtle or catastrophic, depending on the evolving continuity of the equilibrium set (Thom, 1975). (In a subtle bifurcation the equilibrium set is continuously defined, whereas in a catastrophic bifurcation, it develops a discontinuity). Consider how these modes naturally arise.

### Nest construction

Each spring, termites develop a sensitivity to a pheromone secretion in their waste. Once this waste has been deposited, atmospheric diffusion of the pheromone creates a gradient field that can "orient" nearby insects. The recent deposit lies at the center of the diffusion field; technically it can be referred to as an equilibrium point where the gradient goes to zero. Each deposit temporarily defines the spatial location of an equilibrium point in relation to the global structure of the pheromone field.

The diffusion field spreads out in accordance with Fick's law, which states that the rate of transport is linearly proportional to density and relates the rate of flow to the gradient of the field. As time passes, the amount of pheromone at the equilibrium point decreases (a dissipative process), scaling the field gradient accordingly. Eventually the concentration of pheromone at the equilibrium point approaches that of all points in the gradient field, at which time the system is at equilibrium. At equilibrium there are no gradients and, therefore, no local equilibrium points. This means that at equilibrium the global dynamic is identical to the local dynamic. If only a few insects participate in nest building, the depositing is so infrequent that the pheromone field of recent deposits dies out and goes to equilibrium before another insect can be influenced by the deposit.

*Perceptual couplings and thresholds.* The behavior of insects during nest construction is organized by an evolution of relatively stationary attractors in the pheromone field. A change in the attractor layout induces an instability in the pheromone-flow pattern. Following the reaction mechanism described in the previous section, this instability then drives the system to a state of greater order, as instability begets self-organization.

The insects relate to the pheromone field through a perceptual coupling that circularly maps kinematic descriptions of the pheromone field into the insect's nervous system, and back into the world of kinetics through the insect's actuators. The perceptual coupling links the insects to the pheromone field only in regions of the building site where the pheromone concentration exceeds a critical activation threshold for their perceptual system (see Figure 4). Once insects enter an activation region they follow paths mapping the streamlines<sup>3</sup> of the pheromone field. The insects' journey up the gradient terminates ultimately at the region of maximum concentration – the equilibrium point. On arriving at the equilibrium point the insects deposit their waste. With the loss of their waste material the insects lose their pheromone affinity and cease to be oriented by the pheromone field. The pheromone affinity returns with the build-up of new waste material in the insect.

The role of perceptual thresholds in the insect system is similar in some respects to the role of force threshold in the magnetic-field example illustrated earlier in Figure 1. Just as the force field may be too weak to move a particle (Figure 1a), the pheromone concentration may be too weak for the insect to detect. As is the case in Figure 1b, if the pheromone concentrations are far apart, then they will not interact with each other in regions above threshold. Finally, as we shall see below, the case of two attractors that are close enough that their interaction is above threshold will, just as in Figure 1c, result in a competition that leads to nonlinear behavior. Next, we describe the four modes exhibited during the nest-building process.

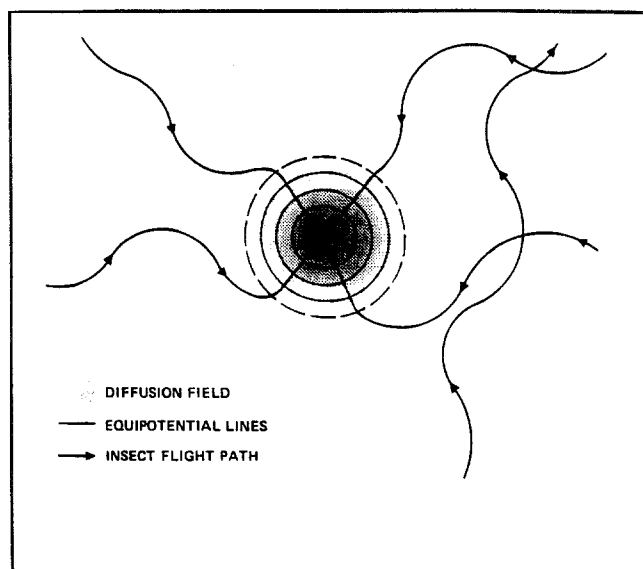


Fig. 4. "Perceptual limit" of the field defines a symmetry-breaking mechanism; insects in areas in which the pheromone gradient falls below the perceptual limit exhibit no correlation among their motions; they are at equilibrium; insects in areas in which gradient is above the perceptual threshold exhibit correlations between their motions; they are displaced from equilibrium (adapted from Kugler & Turvey, 1987).

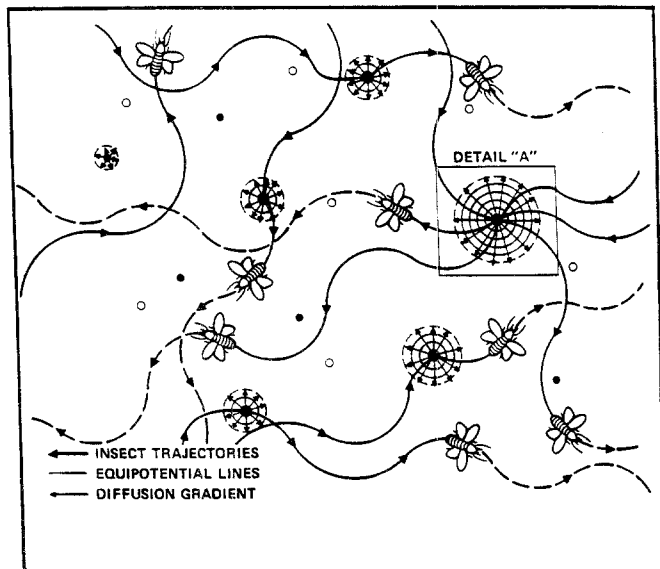
*Random deposits: A reversible equilibrium mode.* In the first phase of nest building, the motion of insects is only weakly coupled to the motion of pheromone molecules, since only very small localized regions contain enough pheromone to exceed an insect's perceptual limit. The result is a random-depositing mode of nest building. The motion of the insects is essentially independent of the motion of the pheromone molecules. In the absence of regions of high concentrations of pheromone, the depositing pattern is dominated by random reversible fluctuations. The gradient dynamic on the pheromone field plays no role in the organization of insect motion. Thus, the motion of the insects is at equilibrium with respect to the pheromone field when the pheromone gradient is uniform. In the equilibrium mode, the motion of each insect is independent of every other insect; no preferred deposit sites orient insect flight pattern. Random depositing persists as long as a small number of insects participate in nest building.

This mode corresponds to the type of behavior governed by the attractor defined by the Second Law, as discussed in the previous section. There is no change in the order of the system, since the pheromone field remains uniform. The maximum entropy equilibrium point is the only attractor in the field.

*Pillar construction: A linear near-equilibrium mode.* As more insects participate, the likelihood of an insect passing an active site increases. Beyond a critical number of participating insects, the equilibrium condition of the flight pattern breaks down, and some preferred deposit sites begin to emerge on the surface of the work space (see Figure 5). Increases in the rate of depositing on preferred sites increase the size of the gradient field that attracts the insects, which, in turn, increases the rate of depositing ... and so on. As the size of a deposit site grows, long-range coordination patterns begin to develop among the flight patterns of insects, as more and more insects begin to orient their motion to the pheromone field. The result is an autocatalytic reaction, resulting in rapid amplification of material deposits at points of highest pheromone concentration (equilibrium points). As the autocatalytic reaction continues, a pillar begins to be shaped out of the waste deposit (see Figure 6). The pillar is constructed at the location of the equilibrium point, with only the top of the pillar remaining active.

During pillar construction, active deposit sites contain only one equilibrium point. While multiple active deposit sites can exist in the workspace, none contains multiple equilibrium points. In this construc-

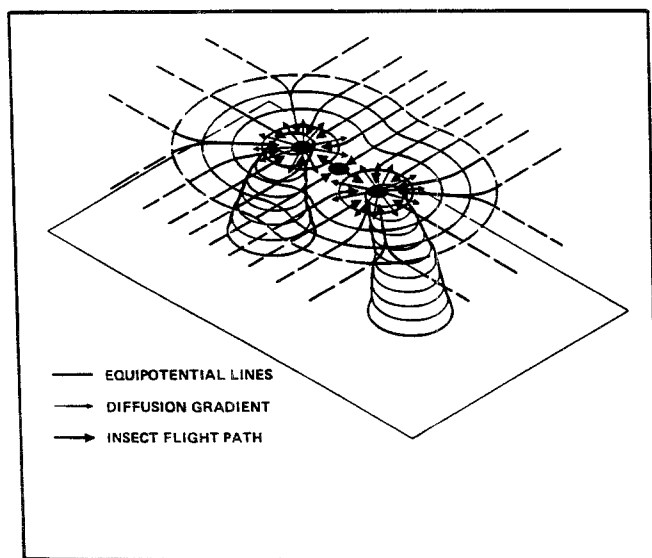
<sup>3</sup> A streamline is a line of flow that is everywhere orthogonal to the isopotential contours of a field. In the case of a gradient field the streamline defines a path of the steepest gradient.



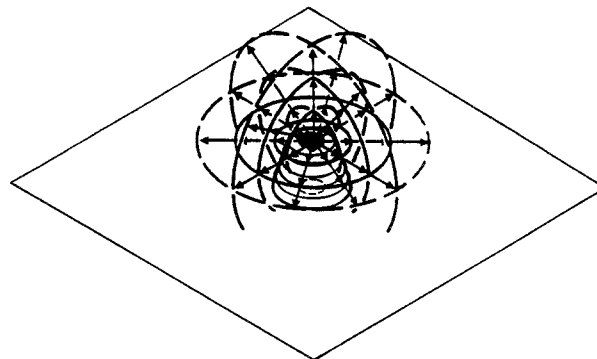
**Fig. 5.** Development of preferred sites: the development of a preferred site marks a sudden transition in the correlation state of the insect population; as the size and number of preferred sites increases, correlations begin to develop between the insects' external coordinates of motion; the insects' behavior is no longer at equilibrium (independent of one another), it evolves into nonequilibrium states exhibiting increased correlation (adapted from Kugler & Turvey, 1987).

tion phase, all pheromone gradients above the insect's perceptual threshold contain only one equilibrium point. In these localized regions pheromone flows relate linearly to driving forces generated by the chemical potential.

*Arch construction : A nonlinear far-from-equilibrium mode.* As the size of the active gradient regions enlarge, however, competitions begin to develop between gradients generated by neighboring equilibrium points (pillar sites). This competition occurs when the active portions of the two gradient fields begin to overlap. Saddlepoints organize the interface boundary separating the two gradient fields. The saddlepoint is a fixed-



**Fig. 7.** Building an arch: the emergence of the saddlepoint further displaces the system from equilibrium; the organizing influence of the saddlepoint extends the insect correlations to a region defined over the two pillars (adapted from Kugler & Turvey, 1987).



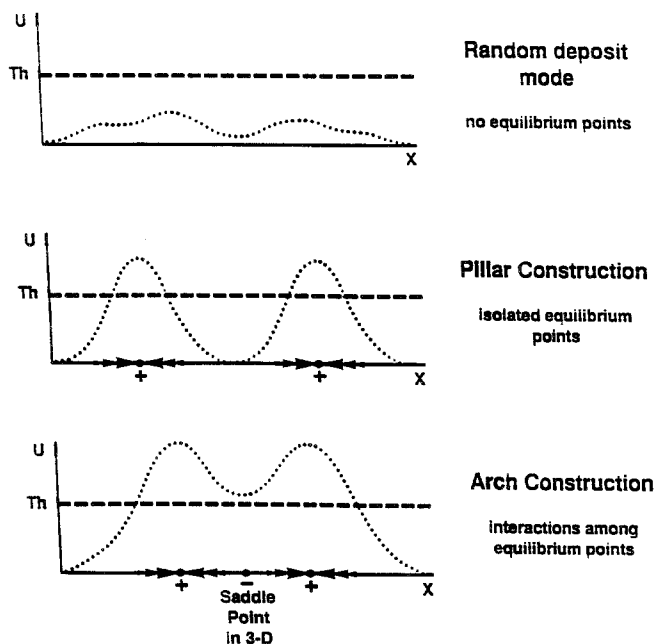
← DIFFUSION GRADIENT  
— 2-D EQUIPOTENTIAL LINES  
— 3-D EQUIPOTENTIAL LINES

**Fig. 6.** Building a pillar (adapted from Kugler & Turvey, 1987).

point property that defines a global symmetry (invariant solution) that relates the two local gradient fields. The saddlepoint forms a set of field constraints that are used by the insects in the construction of an arch (see Figure 7).

The saddlepoint displaces the system further from equilibrium by extending the characteristic size of the correlations among insect motions. Near equilibrium the correlations are restricted to local regions near pillars. In contrast, in far-from-equilibrium conditions the characteristic length for correlations include larger (more global) regions containing multiple pillars. In this region the linear relaxation dynamic that is organized by a single equilibrium point is replaced by a nonlinear dynamic organized by competitions among multiple equilibrium points. The competition is greatest at the saddlepoint where the forces change directions. At the saddlepoint region the linear force-flow dynamic of pillar construction is replaced by a nonlinear force-flow dynamic that results in the construction of arches (see Figures 8 and 9).

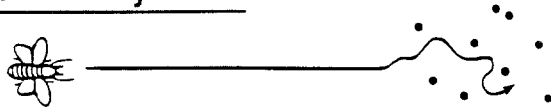
## POTENTIAL FIELDS



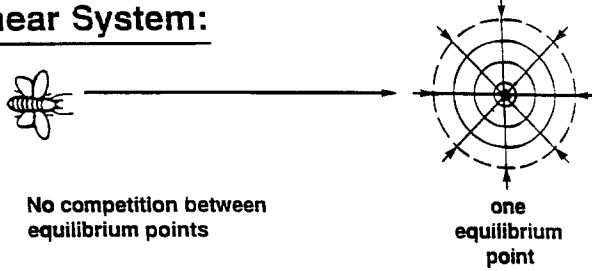
## Integrated Global Structure

**Fig. 8.** Comparison of the potential fields for the random-flight mode, the pillar-building mode, and the arch-building mode.

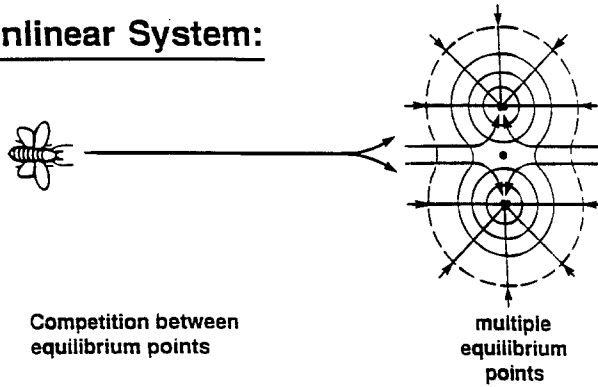
**Random System:**



**Linear System:**

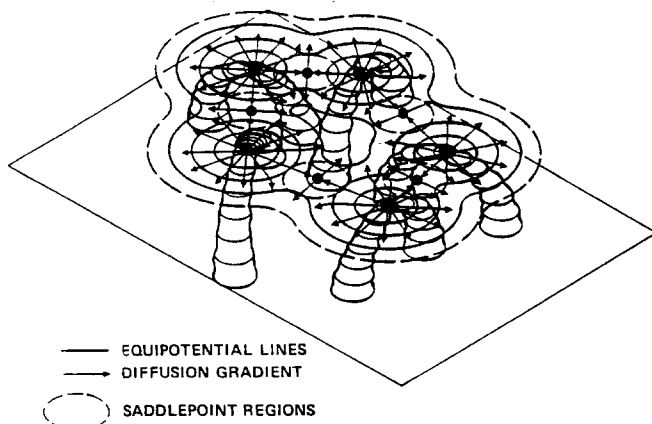


**Nonlinear System:**

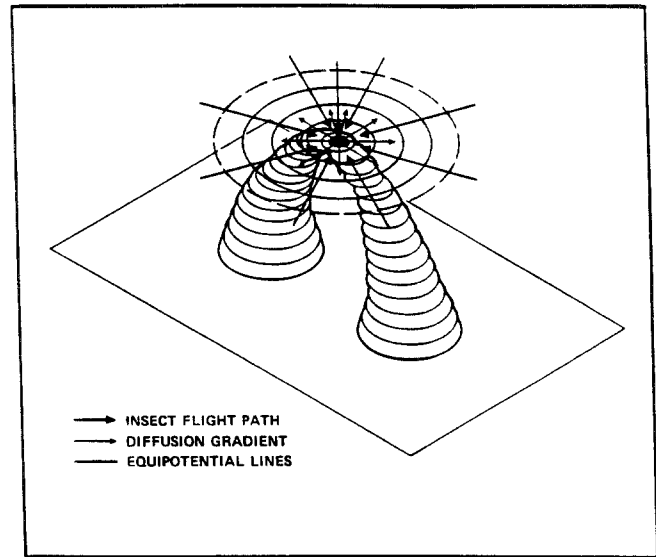


**Fig. 9.** The equilibrium regions partitioned by the perceptual threshold for the random flight (no equilibrium points), pillar construction (isolated equilibrium points) and arch construction (multiply interacting equilibrium points).

The saddlepoint breaks the symmetry of the location of deposits by introducing an inward bias in the direction of the competing equilibrium points. The addition of this bias adds a curvature to the pillar that results in the construction of an arch. The saddlepoint defines a common (invariant) solution that simultaneously satisfies the local gradient field constraints of both pillar basins. Thus, the saddlepoint is a higher-order attractor defining a symmetry that is invariant over two competing gradient basins. The construction of the arch emerges out of the more global symmetry of the saddlepoint. The saddlepoint symmetry defines a set of constraints that insects can use to coordinate their motions in relation to two pillars.



**Fig. 11.** Emergent saddlepoints are used to build a dome (adapted from Kugler & Turvey, 1987).



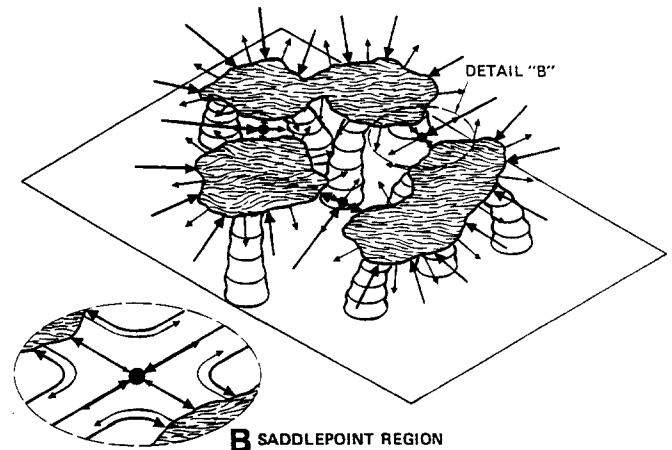
**Fig. 10.** Completion of the arch and annihilation of the saddlepoint (adapted from Kugler & Turvey, 1987).

*Dome construction: A return to the equilibrium mode.* The completion of the arch is associated with the coalescing of the two pillar equilibrium points with the saddlepoint, resulting in the annihilation of the saddlepoint and the emergence of a single equilibrium point at the top of the arch (see Figure 10). Gradient flows emanating from the new equilibrium point interact with neighboring gradient flows, resulting in the emergence of an intricate pattern of new saddlepoints. These saddlepoints organize a new gradient layout that, in turn, provides new constraints which coordinate the construction of a “dome” (see Figures 11 and 12).

Upon completion of the dome, the far-from-equilibrium condition is annihilated; this results in a return of the equilibrium mode. A new construction cycle then begins, starting with the random-deposit phase on the surface of the dome. (Figure 13). The system begins another cycle through the sequence of construction modes (Figure 14):

*random deposit* → *pillar construction* → *arch construction* → *dome construction* → *random deposits ... and so on.*

There are several aspects of this example to be emphasized. First, the nest-building cycle of these termites typifies the generic mechanisms of self-organization. Each mode is specified by a unique layout of attractors. The transitions



**Fig. 12.** Development of a dome (adapted from Kugler & Turvey, 1987).

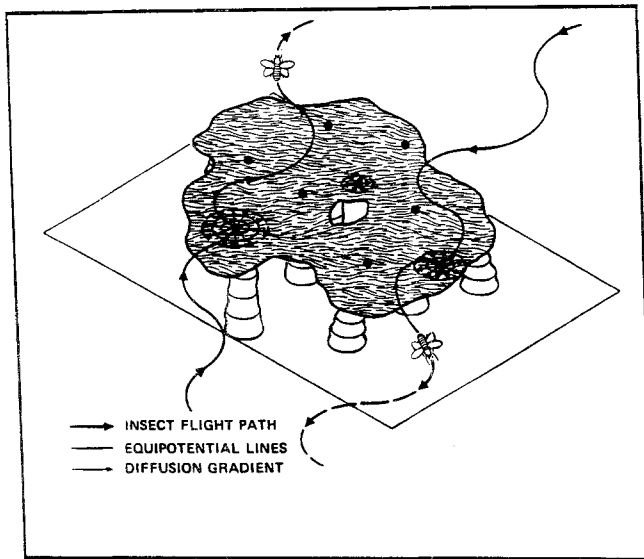


Fig. 13. Upon completion of the dome, the building phase returns to equilibrium, beginning once again with the random-flight phase (adapted from Kugler & Turvey, 1987).

between behavioral modes occur when attractors are either created or annihilated. Also worth noting is the circular nature of the processes that sustain the construction of the nest. The insect behavior both contributes to, and is oriented by, the pheromone field. Insects contribute to the pheromone field through their frequent deposits. The structure of this field, in turn, orients the insects' depository activity. In this regard, the nest-building system is exemplary of a self-reading and self-writing system (see Figure 15). The circular linking of the replenishing and dissipation of pheromones through coupling forms a new kind of "engine", one that goes beyond mere energetic (i.e., thermodynamical) connections. Because the circular closure of the cycle depends on information flows as well as on energy flows, we have a closed thermodynamic-epistemic engine cycle (Figure 16; Kugler & Shaw, 1990): force field (muscular activity) → flow field (pheromone-control constraints) → force-field (muscular activity) → flow field (pheromone-control constraints) ... and so on. Alternatively, the engine cycle can be described as an action → per-

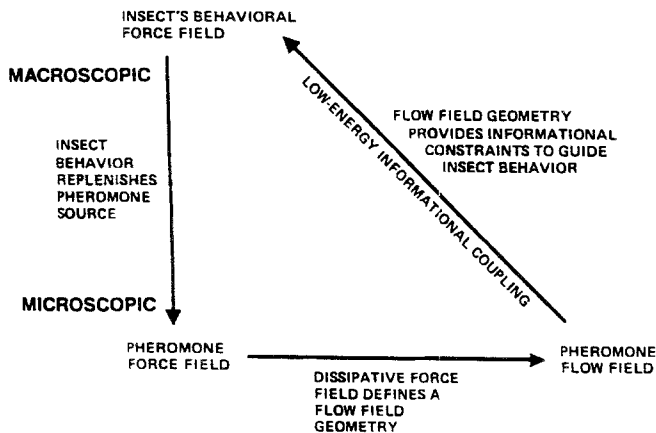


Fig. 15. Self-reading, self-writing, self-organizing information system (adapted from Kugler & Turvey, 1987).

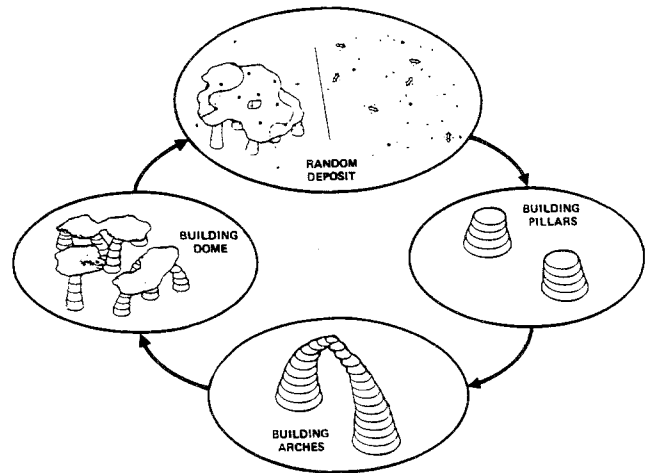


Fig. 14. Circular ring of building phases: each phase is dominated by a small set of critical (degenerate) states that organizes the chemical flow fields; these flow portraits provide the control constraints that orient the insect's motion (adapted from Kugler & Turvey, 1987).

ception → action → ... etc. cycle (compare the cycle depicted in Figure 17 with the cycles depicted in Figures 15 and 16).

Finally, it is important to emphasize that the nest-building system is a thermodynamically open system. As was pointed out in the previous section, self-organization is possible only when a system is open to the flow of energy and mass. Thus, the thermodynamic pump that adds a higher grade of energy to the system (local regions of high pheromone concentration) plays a critical part in any self-organization process. In this case, the part of the pump is played by the insects' depositing of waste in the pheromone field. The construction of the thermodynamic pump is the greatest challenge for any evolutionary system.

Similarly, like an epistemic engine, information is also "pumped" into the system. An understanding of how the informational linkage arises and works in completing this

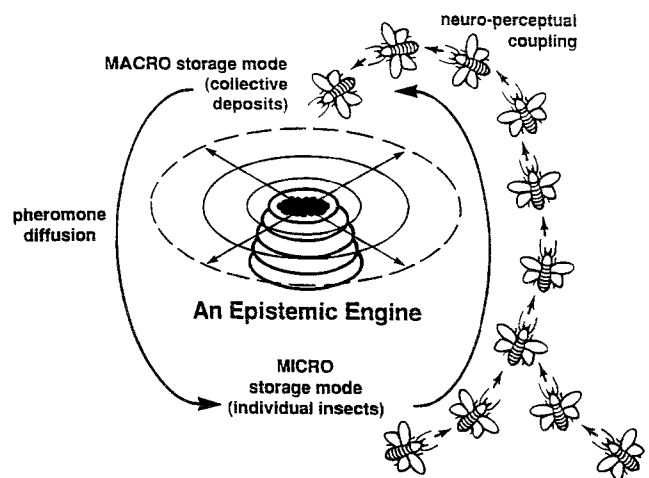


Fig. 16. The individual insects define micro storage modes for the pheromone; the active deposit on the pillar defines a macro storage mode; the insect's transport of the pheromone to the top of the pillars is an escapement process (micro → macro transport) and the diffusion process that distributes the pheromone from the top of the pillar to a uniform distribution is a dissipative process (macro → micro process).

circularly causal system is equally challenging to any cognitive psychology. Such a mechanism may provide new (e.g., ecological) foundations to cognitive psychology.

### *Primacy of informational linkages*

Like the falling leaf, the insect-nest example provides an effective illustration of the properties of self-organization discussed in the previous section. However, it also possesses an important property that distinguishes it from the leaf and the magnetic-field examples. While inanimate physical and chemical systems are governed by a force field, the insects are guided by an information field. The distinction is a critical one, and will be of prime importance in the discussion of intentional dynamics. Intuitively, physical systems go where they are pushed. The forces acting on the system determine its behavior. The magnetic-field example presented earlier is a prime illustration of a force-dominated system. In the insect example the pheromone field is not pushing the insects toward the attractor regions. There are no significant forces from the pheromone field relative to the mass of the insect. Instead, the pheromone field provides the insects with information that specifies where the building sites are located. The insect can detect this information and then use its own on-board energy supply (i.e., its action system) to travel in the direction of the attractor. Thus, the energy that is propelling the insect is generated internally, whereas in physical systems the energy guiding the system is a direct result of an external force field acting on the particle in question.

The difference between the two systems can be characterized as follows: the behavior of inanimate systems is lawfully determined by a force field, whereas the behavior of animate systems is lawfully specified by an information field. The lawful determination of information was anticipated by J. J. Gibson (1979) in his pursuit of a kinematic-field analysis of optical-flow couplings. Gibson's methodology focused on the physical and functional significance of non-force interactions. By focusing on non-force field descriptions, a natural transition can be made from the physical theory of self-organization to a theory of self-organizing information systems.

What relevance does the analysis of the insect-nest example have for the understanding of intentional behavior? Before this question can be answered, some general characteristics of intentional behavior need to be described.

## Challenges posed by intentional systems

### *An inventory of teleological mechanisms*

Teleological determinism is the philosophical view that assumes that goals, as future states, somehow act causally backward in time to guide systems down goal-paths. Many philosophical analyses have rejected the thesis of temporally backward causation because it violates natural law to have an effect precede its cause (Russell, 1945; Braithwaite, 1953; Taylor, 1966; and especially Woodfield,

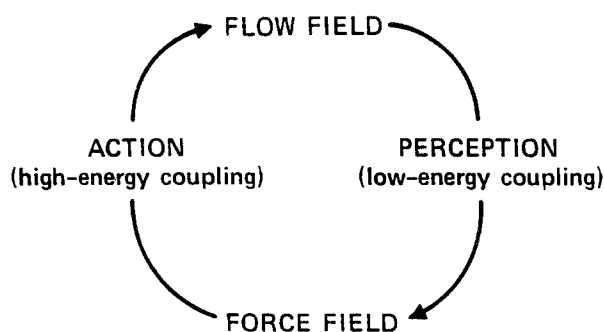


Fig. 17. Perception/action cycle. A circular causality of self-assembled flows and forces (adapted from Kugler & Turvey, 1987).

1976). Such a thesis can be held only if one repudiates the principle of state determinacy.

*State-determinacy.* In mid-century, cybernetic approaches attempted a scientific reformulation of the problem of intentional systems by identifying goal determinacy in terms of state determinacy (Rosenblueth, Wiener, & Bigelow, 1943; Ashby 1952, 1956; and especially Sommerhoff, 1950). It was hoped that this ploy would mechanistically capture the essence of intentional behaviors while, at the same time, avoiding the pitfalls of teleological determinism. There is a danger in mechanistic approaches, however, for they typically attempt to reduce final causes (goal-states) to initial conditions plus efficient causes (laws); (e.g., the setting of setpoints by an extrinsic agent rather than by the system itself). Thus such attempts fail because they regress the problem of intention to the problem of determining how and for what purpose the system was designed. This failure has led most scientists to reject out of hand all forms of teleological determinism.

The argument against teleological determinism, however, may be overstated. Perhaps, one might champion a weaker, acausal version of teleological determinism that avoids the scientifically suspect thesis of temporally backward causation. Weir (1985) offers compelling arguments for the provocative thesis that goal-directed systems are directed by goals rather than being merely self-directed toward goals, as cybernetics would have it. By this change in emphasis, Weir avoids attempting a logical reduction of final causation to efficient causation as others typically do, and takes a different tack than state-determinacy arguments. He argues that goal-directed behavior can be formally distinguished from other behaviors by its characteristic mathematical structure and pattern. A brief account of Weir's argument follows.

Strong teleology implies temporally backward causation, where an action's cause (its goal) comes later than its effect (its path). This perplexing view abrogates the classical state-determinacy principle that requires future states to be caused by past states. Yet, whereas a billiard ball follows a path determined by its past events (motion states), we recognize, in some sense, that a hungry predator follows a path determined by an anticipated future event (capturing its prey).

Mathematically, state determinacy implies analyticity. From an infinitely small section of an object's past or future motion path, given by a differential equation, the rest of the path can be analytically projected by integrating the equation. For three centuries analytic projection in the temporally forward direction has provided the best formal description for explanatory laws of motion mechanics. Therefore it is only natural to

attempt to use analytic projection in the temporally backward direction as a formal description for corollary explanatory laws of action mechanics. Unfortunately, this strategy encounters serious problems. Let's see why.

*Path determinacy.* Corrections introduced into goal-directed actions show up as path bifurcations that are not analytically continuous with either past or future states; and yet action paths are shaped in anticipation of future goal-states. To explain anticipatory control logically requires goal determinacy. This has convinced many theorists to move from state determinacy to path determinacy in order to accommodate anticipatory goal constraints (Rosen, 1985).

Path determinacy is the view that final causation might be expressed lawfully by designing goal paths, according to a minimum principle, backwards from the system's final condition to its initial condition. How might this be done? This approach grows naturally out of a form of classical mechanics known as variational mechanics (Lanczos, 1970). In the ordinary calculus one seeks to express state determinacy by finding the tangent that lies at the minimum (or maximum) to a function (a curve) at a point. Hence by differentiation one selects from all points on a curve the point that is the extremum of interest. By contrast, the calculus of variations provides a method by which one can compare path integrals (i.e., curves) and select from among the one that is minimal. On the assumption that a path is a minimal curve just in case it is the intended goal path, many theorists were persuaded that where the ordinary calculus of differential equations modeled time-forward causation, this complementary calculus of integral equations provided a way to model backward causation. Since it operated on paths (integrals of curves), while the other operated on points (states of a tangent vector), it seemed to make explicit a principle of path determinacy. It is now accepted that no prescience is implied by this path-determinacy approach, since it reduces on all occasions to a formulation in terms of differential equations. Hence path determinacy provides no theory of goal determinacy, but qualifies only as a variation on the state-determinacy theme since the two are mathematically equivalent. There is, however, a further alternative formulation, which Weir attempts.

*Germ determinacy.* If forces coordinate action paths with their origins (initial conditions), then what coordinates them with their goals (final conditions)? It does not help merely to say that goals themselves must somehow be responsible for coordinating paths, for the issue is not whether, but how, they do so. If postulating backward (efficient) causation is metaphysically bizarre and logically perplexing because it inverts the presumed order of cause and effect, then we must seek another way in which goals might constrain actions. For this we need to replace the notion of an analytic function with another mathematical concept – that of a germ. To do this moves us from the relatively tame realm of linearly continuous mathematics to the wild regions of nonlinearly discontinuous mathematics.

A goal path, Weir proposes, is really a bundle of virtual paths that may agree (are defined by the same mapping and show the same analytic continuation) up to a point of discontinuity, called a *bifurcation point*; after which they might bifurcate into a collection of separate paths – with each path representing a different possible realization of the goal. This bundle of virtually separable goal-directed paths is called a *germ*, and is not a function, since at the bifurcation point it is one-to-many (Auslander & MacKenzie, 1977). Hence the germ is the formal cause of a goal-directed path, that is, a dynamical principle that expresses nondeterministically the distinctive shapes that paths may assume.

Weir proposes that goal determinacy is mathematically identical to germ determinacy – a concept that imputes a special role to perception in constraining goal-directed behaviors. Actors perceive the transformability of current action states, despite thwarts, into future goal-accessible routes precisely because they perceive the germ of the generalized action potential specific to a given goal. The germ, as the dynamical principle governing a teleological system, although not a function itself, contains all of the analytic and nonanalytic mappings from past states to goal states.

In summary, Weir argues that goal-directed behavior is nonanalytic, bifurcatory behavior requiring germ determi-

nacy rather than state determinacy, or even path determinacy, for its explanation. This implies that a goal is not a designated final state to be reached by a system, but a distinctive way of the system reaching a final state over one of several optional paths, given goal variation. Finally, goals play an active role in the control of behavior because their variation is perceptually projected directly into corresponding changes in the action-control variables, which then shape the actor's path through efficient causes. For our purposes, we should emphasize the argument that goal determinacy, when viewed at the goal scale of germ determinacy, promises a bird's-eye view from which to appreciate intentional dynamics – a view unavailable to the more local scales of path determinacy and state determinacy.

This brief summary prepares us to appreciate the full significance of Weir's (1985) solution to the mechanisms of teleological determinism. According to him, goal-directed behavior "... necessarily involves explaining the behavior that occurs by reference to some behavior being perceived to bring about the goal. And if behavior is brought about because of this perception, then the behavior is goal-directed" (p. 121).

But how might a behavior be perceived as bringing about goal? Does this mean paradoxically that the future somehow controls the present? Perhaps Weir had something like the following in mind. No paradox analogous to "backward-causation" is encountered if we treat perceptual information as if it flowed temporally backwards in relation to the temporally forward flow of action paths (see Shaw, 1987, and Shaw & Kinsella-Shaw, 1988).

It is important to distinguish between systems with perceptual abilities that intend as opposed to those that merely have intentions. Both kinds of system exhibit intentional dynamics, in Weir's sense, but are distinguished by how they do so. We shall term *cognitive* the capacity to intend for the reasons given next. Just as we can take an ecological approach to perception and action, so we can also to cognition.

### *Intending systems as opposed to systems merely having intentions*

The magnetic-field example above identified how an isolated system's behavior to be governed by attractors. There was no capacity for self-organization in this isolated system. By contrast, in the falling-leaf example, we saw how an open system can reorganize into higher-order modes of behavior as more and more energy is pumped into the system vis à vis an escapement. In extending our analysis of self-organizing systems to nest-building by social insects, we saw that higher-order modes of behavior can also emerge from the detection of goal-specific information that controls the energy escapement. Such systems, however, exhibit goal-directed behavior without having the ability to formulate intentions in the cognitive sense – that is, without being able to intend. They are systems that exhibit intentional behavior without intending the behavior.

Explicit choices of goals are not made by such systems, although ties between attractor influences may be broken by random variation (e.g., perturbation of initial conditions). We might call this *implicit goal selection* as, e.g., when random molecular perturbations temporarily alter the pheromone gradient between two pillar attractors so as to favor one or the other. The termite's goal-path tie gets broken implicitly by environmental (external-state) perturbations and not by an explicit (internal-state) choice on the part of the insect.

Thus, a system with the ability to make choices must have the capacity for intending and not just for perceiving and moving. We offer, then, the following hypothesis on the nature of intending. We identify intention with an operator that selects, from among all possible final states of a system, a specific final state to be the goal. Goal selection, we shall argue, is the sensitivity of a self-organizing system to nonlocal constraints that have determinate local effects – such as breaking ties between competing attractors. By selecting, implicitly or explicitly, among possible final conditions, intentional systems go beyond those systems that operate only under the constraints of actual final conditions. Final conditions are actualized by the application of natural laws to existing initial conditions. Systems that exhibit intentional behavior satisfy the above stipulation for the existence of an intentional operator. But to be capable of intending requires something more.

A system intends a particular final condition (goal) if from among the possible initial conditions it selects the one that permits attainment of the specified final condition under the existing law domain. Hence intending systems, unlike merely intentional systems, are capable of true choice behavior. Intending is rational when the choice of the initial condition follows consistently from the prioritizing of needs or values. However, the property that is unique to an intending agent is that it can go against the gradients specified by the information field.

Our purpose in this paper is not to consider the problem of why certain intentions get formulated, but to suggest a law-based explanation for their behavioral efficacy; namely, that intentions identify a higher mode of system organization whereby a new attractor dynamic is defined. This occurs when attractors are created or annihilated in the state space of the self-organizing system by means of energetic and informational couplings equivalent to those found in the nest-building example. The rest of this paper explores this topic.

*The general role of the perceiving-acting cycle:  
To conserve intention*

Whenever actions succeed on purpose rather than accidentally, current information must specify what is to be done next over and over again until the goal is reached. This mutual and reciprocal support that information-detection processes and action-control processes give each other is the job performed by the perceiving-acting cycle. Let's examine more closely how it works.

With each step closer to the goal the information must become ever more specific, thereby tightening the reins on

how the action path unfolds, until ultimately, at the moment of accomplishment, the path becomes uniquely defined. The elimination of the degrees of freedom for action-control options corresponds to a progressive reduction in the number of paths in the germ from which action paths are selected. Our improving prospects for reaching the goal at some future space-time location are noticeable in the here and now. In this way, the successful action of the perceiving-acting cycle is to distill from all possible paths, in the bifurcation set emerging from the germ, the path that best (con)serves the directing intention.

In field-theoretic language, the felicitous perceiving-acting cycle follows a geodesic, or streamline, through the ecological field. Thus it defines the optimal goal path, or the near-optimal one if it is less successful in avoiding thwarts, or less accurate in resolving goal-specific information, or less skillful in controlling the action than the ideal. Biological evolution does not require perfection. Nature is pragmatic rather than idealistic, demanding only that the goal path generated by this cycling intention be tolerably suboptimal so that life-supporting needs are met and life-threatening situations avoided. Psychological development and health may require more: namely, that information be gathered in the process, or that stress be reduced, affections satisfied, and tastes pleased.

*Special role of perceiving: To furnish anticipatory information to intention*

Perception provides spatiotemporally “remote sensing,” acting as a kind of “early warning” device that informs the system of pending goal variation. There is information available in the present that lawfully specifies upcoming future events. Evidence that perception can indeed cause projection of future trends is provided by time-to-contact research on the perceived imminence of collision with obstacles, as provided by Schiff (1965) and Lee and his colleagues (e.g., Lee, 1976; Lee & Reddish, 1981; Lee, Lishman, & Thomson, 1982) and Shaw and his colleagues' research into the perceptual information for the aging of faces and other objects (see Mark, Shaw & Pittenger, 1988, for a review). This body of research suggests that perceptual-information flows are temporally antecedent to the consequent tuning and execution of actions. This relativity of rates accounts for both the apparent temporal backward flow sometimes attributed to goal-specific information and for the temporally flow always attributed to the mechanical energy producing action paths (Shaw & Alley, 1985).

Like fish swimming in a current-free pond, we detect in information flow a counter-current to our action flow, not because information really flows, but because we really move toward goals.

*Other similar views*

We might ask how this view of goal determinacy as germ determinacy compares and contrasts with other contemporary views. On the one hand, it contrasts with Sommerhoff's

(1950) view in locating control in the perceiving-acting cycle rather than in some logico/physical state of affairs. This makes perceptual sensitivity to available goal-specific information of foremost importance, with mediating mental states (desires, beliefs, internal representations) taking a contributory, but insufficient, role in the explanation of goal-directed behaviors.

This approach also puts one in mind of Gibson's (1979) notion of an intentional rule for the perceptual control of action which asserts the conditions that any successful goal-directed system must satisfy. In order to achieve goal  $x$ , then act so as to produce the perception  $y$ . Note that, according to this principle, the invariant in goal-directed behavior is the final condition, which is defined on the perceptual side. The role of action is to control the approach to the perceptually specified goal. It does so by reinitializing the control laws (e.g., self-produced forces) in a manner appropriate to the goal-specific information. The importance of this fact will be brought out below. For now, a simple example will serve to illustrate the idea.

Writing one's signature is an effective context for illustrating the primacy of perception. The specific actions one executes in signing one's name depend upon many factors. The exact muscles used will be a function of one's current posture and the weight of the writing utensil. Furthermore, if there are external disturbances, motor movements will have to compensate for these if the product is to be legible. In all of these cases, however, what remains invariant is the product, not the process. That is, what one's signature looks like remains constant, whereas the exact sequence of motor movements used to produce it does not. Powers (1973) argues provocatively for intentional rules of this sort. Unfortunately, he undercuts his own position by adhering strictly to linear-feedback (state-determinacy) principles.

In the following section, the concepts introduced here will be integrated with the mechanisms of self-organization discussed earlier. The resulting synthesis represents an ecological approach to intentional dynamics that provides one way of attempting to unravel the mysteries of goal-directed behavior without depending solely on internal states (mental acts). The cognitivist who wishes more than this should consult our discussions of why we believe this dual-state (organism-environment) approach is sufficient (Shaw & Todd, 1980; Turvey, Shaw, Reed, & Mace, 1981; Shaw & Mingolla, 1982; Shaw & Kinsella-Shaw, 1988; Kugler & Shaw, 1990).

### The self-organization of intentional behavior

Is it possible to derive a lawful account of intentional behavior in which an information field serves as the guide for goal-directed behavior, just as it did for the insects? The first step toward answering this question is to look at the types of constraint that are operating in intentional systems. The preceding discussion of goal-directed behavior will provide a basis for carrying out this phase of inquiry. The second step is to see if those constraints can be expressed through the generic mechanisms of self-organiza-

tion. The earlier discussion on self-organization provides a background against which to approach this second phase.

### Constraints on intentional behavior

*The perception-acting cycle.* The best way to approach the issue of constraints is through an example. Take a prototypical case of goal-directed behavior: a driver who successfully brings his automobile to a controlled stop when approaching the bottom of a hill. The rolling of a car down-hill, accelerating through gravity, is an ordinary physical motion, while the movement of the driver's leg by a controlled change in muscle tonus to the brake pedal and applying the proper amount of pressure is an ordinary biomechanical movement. But the driver's informed intention to move her leg so as to achieve a final outcome is quite extraordinary, for it depends upon two things that physics and biology ignore: the choice of an intended goal state (e.g., the final velocity of the car) as well as the detection of information (e.g., the optical flow field) specifying in what manner she is to modulate the relevant actuators, that is, through the biomechanical/mechanical linkage of: leg muscles  $\rightarrow$  brake pedal  $\rightarrow$  hydraulic pressure  $\rightarrow$  tire friction/surface friction.

Without the intending being logically antecedent to the movement, no temporary biomechanical linkage would be functionally (physiologically) assembled or sustained throughout the act's required duration; and without the detection of the optical flow that is reciprocally constrained by the act of braking, the intended mode of control could not be monitored, and thus the intended outcome would be difficult to achieve.

Consequently, informed intending, after choosing and anticipating the goal-requirements for action, both assembles and sustains the mechanism for the realization of an action and becomes informed in a sustaining way by perception of the conditions required to achieve the stipulated goal. This mechanism is a cycle of:

*Intending  $\rightarrow$  perceiving  $\rightarrow$  choosing  $\rightarrow$  anticipating  $\rightarrow$  assembling  $\rightarrow$  (acting  $\rightarrow$  perceiving  $\rightarrow$  intending  $\rightarrow$  sustaining  $\rightarrow$  acting ... etc.)<sup>n</sup>  $\rightarrow$  Goal*

This is the familiar perceiving-acting cycle introduced in the previous section. There, it was pointed out that the role of the perception-action cycle in goal-directed behavior is to conserve intention. Thus the role of informed intention, as a constraint on physical motion, is a fact of nature – as undeniable as gravity or a sunset. Since this constraint is not recognized by traditional physics, we might call it an exceptional constraint (Kugler & Turvey, 1987; Shaw & Kinsella-Shaw, 1988). Let us explore further the notion of intention as a constraint.

*Holonomic and nonholonomic constraints.* Generically, constraints restrict the physical degrees of freedom of a system. Traditionally, this can occur in two ways. Holonomic constraints restrict without requiring material instantiation. Hence they can be expressed functionally as a relationship among coordinates, and thus do not materially alter the system. Typically, systems that are governed by

holonomic constraints are called *law governed*, since laws are not materially instantiated. For instance, the trajectory of a projectile moving through the air is constrained holonomically by the laws of physics. By contrast, nonholonomic constraints are able to restrict trajectories in state space only because they are physically instantiated – they require some mechanism that materially alters the system. These types of system are often called *rule governed*, since they require rules that are independent of laws to constrain behavior. An example is a computer program, whose behavior (i.e., output) is nonholonomically constrained by the lines of codes that are materially instantiated within the degrees of freedom associated with the electron states that constitute the computer’s memory.

In the issues separating a law-governed account from a rule-governed account of the intentional behaviors of complex systems, one stands paramount. Is an intention, or the goal it selects, a holonomic or a nonholonomic constraint? If intentions are holonomic constraints, then no mechanism is required beyond the one that exploits laws relating energy and information in some specific way. In such a case, one might argue plausibly that through evolution or through learning organisms come to exploit existing laws very effectively in achieving their goals – without necessary recourse to rules of behavior or “internalized” models of goal paths, etc. If this is the case, then the insect-nest example may be a good model for intentional behavior since the manner in which the nest is constructed is based on lawful specification provided by the pheromone field, not on a “mental model” of the plan for building an arch. On the other hand, if intentions are nonholonomic, then something like cognitively internalized models of the environment and the actor’s place in it would have to be assumed because rules require such mechanisms in order to be applied.

On the face of it, from a classical external-frame perspective, it appears that a goal (or its intention) can constrain in both ways. It acts holonomically whenever the organism acts like an inanimate particle by following the external potential gradient (e.g., a rock rolling down a hill and hitting a tree). On the other hand, it acts nonholonomically whenever the system acts animately against an external potential gradient (e.g., a person running down a hill accelerating by gravity, but braking and stopping short of the tree).

Abstractly, in the external-frame perspective, a system is holonomically constrained by a goal over those intervals of the goal path where the internal potential is inoperative or in a stationary process. These will be those integrable (open) intervals of the goal path between choice points. A system is nonholonomically constrained when its behavior must be controlled across choice points. These will be those (closed) intervals that include choice points. Choice points act as nonintegrable constraints and denote regions in the exterior frame where the goal-path curve becomes nonanalytic (discontinuous). How might this happen?

A system with an active nonstationary interior gradient can be thought of, mathematically, as depositing singular points along its trajectory in the exterior frame where choices may be made (e.g., to brake, change direction, speed up, or slow down). Control decisions arise at those

points along a trajectory at which the system must inject a sustaining “squirt” of interior field potential to keep moving in the same mode toward the same target, or where it can counter the work done on it by an exterior gradient. Structurally, these points in the field are actually equilibrium points (attractors). Psychologically, they are choice points in that there is insufficient information in the field to define uniquely the future path.

Mathematically, the existence of singular points (bifurcation points, equilibrium points, or attractors) represents regions in the external frame where the goal-path geometry becomes compact, in the sense of hiding additional (internal) degrees of freedom at singular points along the path. Because these compact singularities determine the point of contact between the two frames, there is no way of integrating the two potentials, and thereby treating them as equations of constraint. Normally, these equations would simply be added to the equations of motion (by elimination) and the resulting system of differential equations solved (integrated) to determine the system’s path of motion. Unfortunately, where goal points occur this cannot be done.

From the external-frame perspective, the problem of modeling intentional systems is exacerbated by the fact that goal constraints must satisfy the final conditions of the differential equations as well as their initial conditions. Thus the value of a goal constraint cannot be found until after the equations of motion for the system are solved (that is, until after the system reaches its goal), yet its value is needed to evaluate the integrating factor before the motion equations can be solved (integrated). Hence a vicious cycle! The integrability problem is compounded when intentions are not stable because this integration process must then be carried out in a piecewise manner between each pair of equilibrium points (choice points). The final yield will be a goal path in the external frame that is a mixture of concatenated holonomic and nonholonomic subintervals.

These concatenated regions of holonomic and nonholonomic constraints are exactly those regions within an open system where entropy is high and low, respectively. To cross regions of low order, the behavior of the system need only be dissipation dominated (controlled by the Second Law) because it is moved by outside forces down the force gradient toward the entropic attractor. By contrast, for the system to cross regions on high order, it must become escapement dominated (perceptually controlled), so that it may move up the information gradient toward the goal. In the dissipation case, work is done on the system by its environment, while in the escapement case, work is done on the environment by the system. Let us define choice points as bifurcation points that act temporarily as if they were equilibrium points or (goal) attractors.

If we can provide a theory relating the internal frame to the external frame, and vice versa, then there is the possibility that constraints that are nonholonomic in one frame might prove holonomic over both frames. This is equivalent to claiming that there is an invariant of motion, a conservation, that carries the system holonomically over these singular regions without a cognitive mechanism mediating the behavior.



Fig. 18. Examples of behavioral modes that populate an average person's work space.

#### *Intention as a "holonomizing" constraint*

Assumption of the minimum principle led to the discovery of one of the most profound results of physical science – the identification of the symmetries which allows a (Lie) group theoretic, and as a consequence, a geometric characterization of the classical conservations. The basis conservations, along with their associated symmetries, are: conservation of total energy (or action), which is identified with a symmetry over time; conservation of momentum, which is identified with a symmetry over space; and conservation of angular momentum, which is identified with a symmetry over direction.

To remain consistent with the inventory already existing, we must formulate the role intention plays in dynamics as a corresponding symmetry. But if reductionism is unlikely, then this symmetry will not be identified with any existing symmetry, but will implicate a new conservation, and possibly other motion invariants. What might a motion invariant for an intentional system be?

This motion invariant should be the informed and controlling intention itself, formally construed as an operator that selects the goal, seeks anticipatory, goal-relevant information, initiates the action, and sustains it to completion down the goal path. In other words, intention as a dynamical variable refers to some quantity or to some qualitative condition that remains conserved if the action is to be successful. Elsewhere, we have attempted to give a mathematically explicit formulation of this conserved aspect of intentional systems (Shaw et al., 1990). The following is a summary of that effort.

Just as the statement "A force is identified with the gradient of some potential which is directed toward the local attractor of the field" applies to inanimate particles to explain how they must get where they are going, so we

need a corollary statement in intentional dynamics to express how animate "particles" (possessed of complex interiors) might get where they intend to go. Provisionally, we might formulate an analogous scientific proposition about informed intentional motion: An informed intention lays down a goal gradient of some generalized potential which is directed toward the local attractor of the ecological field.

A potential is a quantity whose organization, and hence its capacity to do work, is a function of spatial coordinates. By contrast, a generalized potential is defined by a reciprocal (adjoint) relationship that couples two fields. Unfortunately, the coupling of two fields that are not in the same frame is not standard procedure for classical approaches to dynamics. Classical couplings apply only to potentials that exist in a single (external) frame. The challenge is to develop a holonomic description of intentional behavior that bridges the internal field of the organism and the external field of the environment.

#### *Internalization of an evolving attractor set: The embodiment of geometry*

A cognitivist approach to intentional dynamics puts all the complexity of the problem into internal states of the organism (Ullman, 1980; Fodor & Pylyshyn, 1981). An ecological approach to the cognitive aspects of the problem tends to distribute the complexity over both internal and external states, in what might be called a dual-state description (Shaw & Todd, 1980). While intentional behavior carried out by humans seems to be far removed from the building of a nest by a group of social insects, they share certain abstractly equivalent properties that allow them to be modeled in equivalent ways. For instance, just as the insects go through a set of modes representing qualitatively different types of behavior, so a person exhibits different modes in his/her daily life, such as sleeping, eating, working, reading, courting (Iberall & McCulloch, 1969) (see Figure 18). Extrapolating from what was learned from the insect example, it is hypothesized that each mode is constrained by a unique number and layout of attractors. That is, just as in the other examples of self-organization described in this paper, the qualitative properties associated with any given mode of intentional behavior will be defined by the attractor set for that mode. To make this idea clear, let us consider some additional facts about field theory.

Classically, an attractor set is used to define a field external to a particle in motion. An example is the magnetic field described earlier, where the negatively charged particle is described as moving through an externally defined (relative to the particle) magnetic field. But there is also a nonlinear internal field induced locally around the particle that cannot be integrated under the external field through which the particle moves. This is a well-known limitation of the linear-superposition principle of classical field theory (see Sachs, 1973). By definition, this internal field must have its own independent attractor dynamics. For instance, a compass will be systematically deflected as it is moved through the earth's magnetic field. The compass, however, will induce a locally confined, internal magnetic

field that travels with it and cannot be integrated under the external magnetic field. Hence external-(state) field descriptions cannot be reduced to internal-(state) field descriptions, or vice versa. This is the reason a dual-(state) field theory is needed.

Under the external-field description, the internal field is a singular anomalous point in whose neighborhood are hidden degrees of freedom not expressible in the classical mathematics of the external field. In other words, charged particles placed in the field (e.g., compasses) will behave differently inside each other's neighborhoods than they do outside. Fields that have hidden degrees of freedom (internal fields) are said to be *compactified*. The relationship between local and global fields is promoted here to express the relationship between an environment and the organisms acting in that environment. The compacting of an external field by internal-field properties expresses exactly the contributory role perceptual/cognitive variables play, along with physical variables, in codetermining the observed behavior of the organisms. This is what it means to say that an organism, as a perceptually attuned intentional system, is informationally, as well as forcefully, coupled to its environment.

We propose further that these internal-/external-field interactions provide an important and literal expression of the facts about the nature of organism-environment interactions – whether they be “behavioral”, as viewed from the external-field perspective, or “cognitive” as viewed from the internal-field perspective. This dual-field, or ecological-field, perspective expresses all the content of Gibson's (1979) principle of organism-environment mutuality upon which the construct of a psychological ecosystem is founded.

It is useful to bear in mind that the field concept is a generic construct; therefore, the set of contents that support the same field relations and field dynamics are legitimately said to be the same field. Hence it is just as legitimate to use the field concept in psychology as it is in physics, so long as the abstract properties are satisfied. One may think of the field level of abstraction as being as legitimate as the strong simulation claim that two hardware instantiations comprise the same abstract machine so long as the algorithms implemented on them compute the same functions in the same way. If the cognivist accepts this latter modeling proposition, then consistency demands that he/she must also accept the former. What should be recognized are the obvious differences that distinguish this ecological approach to cognition and the traditional rule-governed, abstract machine theory (see Fodor & Pylyshyn, 1981; 1988, in contrast to Turvey et al., 1981, and Carello, Kugler, Turvey, & Shaw, 1984).

Similarly, for both physical and mathematical reasons, it is legitimate to consider the process that organizes in nest-building as arising from constraints that are set up by either an internal or external field depending on the measurement frame. From a social or ensemble perspective, the insects can be viewed as a single collective system, and the pheromone field can be viewed as a field internal to that system. From this perspective, the self-organization occurs in the internal field, not in the external field. The external degrees of freedom define the move-

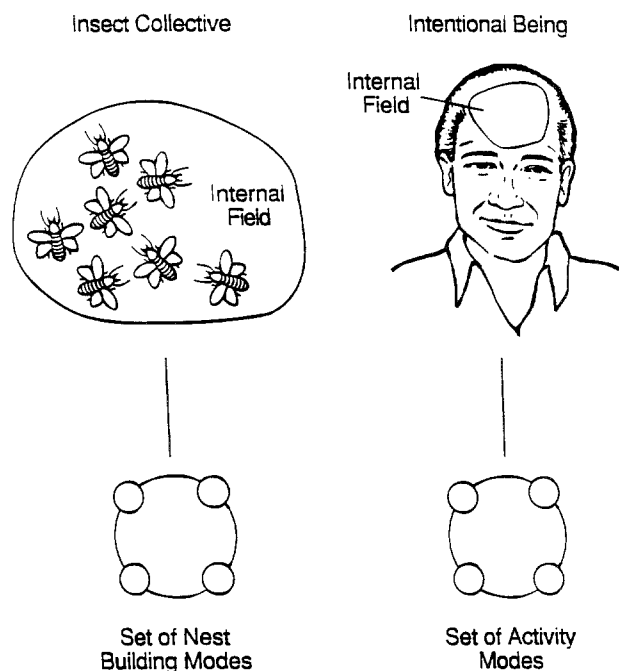


Fig. 19. Examples of open systems with cooperative modes defined on internal degrees of freedom.

ment of the insect society as a whole through an external environment, while the informational (intentional) constraints direct the movement of each insect as a perceptually attuned actor toward its goals.

Taking this step leads to the possibility, illustrated in Figure 19, that an intentional organism is constituted by a similar type of internally self-organizing mechanism. That is, there is an internal field within the organism that is organized by the layout of attractors. These attractors are goal states that act to constrain the system's internal degrees of freedom. The corresponding field, which is determined by the organism's effectivities (i.e., capabilities for action), embodies the internal constraints on action. A change in the number and layout of goal states will result in a change in the field, which in turn manifests itself as a qualitative shift in behavior mode. Referring back to Figure 14, we see that each of the modes illustrated there corresponds to a unique set of goal states that organize the field. All of the generic self-organizing properties that were attributed to the insect colony also apply to this internal field of goal states.

The problem of intentional behavior cannot, however, be relegated solely to an internal-state description. For we saw previously that the phenomenon of intentional dynamics is only apparent at a more global scale – the ecological scale – because goal paths are ecological-field processes whose support depends upon the coupling of two fields – the external field of the environment and the internal field of the organism.

#### *Intentional systems as ecological fields of non-stationary attractor sets*

A single field description, whether it be of the environment (external field) or of the organism (internal field), is only

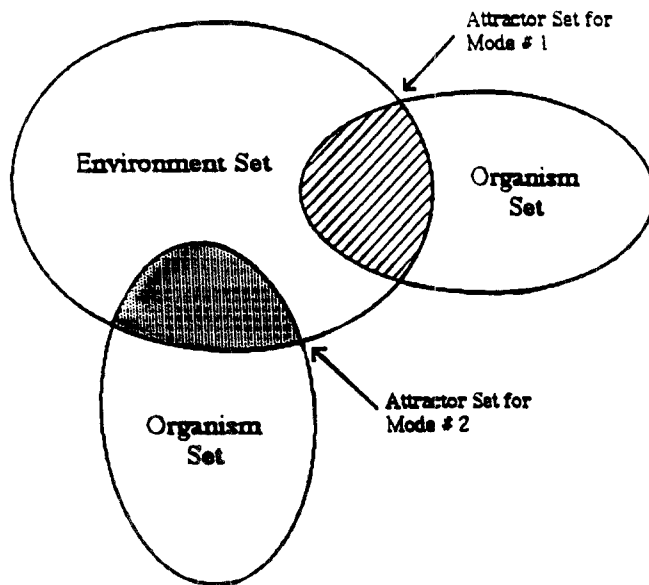


Fig. 20. Nonstationary affordance set: the affordance set for an ecosystem is that set of descriptions that is invariant over the state animal and the environment; since the animal and the environment are both nonstationary, then the common descriptor set (affordances) is also nonstationary.

one of many possible descriptions. An organism can be described in many different ways as a function of the mode it is in (as illustrated in Figures 14 and 18). Similarly, an object in the environment (e.g., an apple) can also be described in several different ways. Some of these are intrinsic descriptions (e.g., the size, color, weight, density, and elasticity of the apple). Others are relational descriptions of the apple (e.g., that it is throwable, edible, etc.). There is an interesting relationship between the various descriptions of the organism and those of the environment.

The possible descriptions of the environment in terms of intrinsic or relational properties form a set, in which no description is more privileged than another. Intrinsic descriptions are no more “real”, in the sense of being more factual, than relational descriptions. In the case of the apple, the fact that it is throwable or edible is a property as legitimate as its color or mass. Similarly, possible descriptions of organisms can be given in terms of intrinsic, as well as relational, properties. These likewise form sets whose members are equally nonprivileged. In the case of an organism, the fact that it can throw or eat apples is as real as its own color or mass. To be scientifically comprehensive, is it not necessary to understand all the useful ways in which the environment or organism can be described? Should scientists arbitrarily restrict their interest to one kind of property than another?

Traditionally, the intrinsic properties of most interest to physics have held a privileged status, not only among physicists, but also among philosophers, biologists, and even psychologists. However, by adopting an ecological scale of analysis, the set of relational properties that lives in the intersection of the organism and environment sets assumes primary interest. These physical relational properties provide an equally interesting and important object of study – one that Gibson (1979) called *ecological physics*.

The decision to approach the problem from a relational perspective is consistent with Gibson’s (1979) principle of organism-environment mutuality. Moreover, the primary ecological field process, the perceiving-acting cycle, is a dynamical relational construct (Shaw et al., 1990). Consequently, any analysis of intentional behavior must focus its efforts here.

This intersection of organism and environment sets represents what Gibson (1979) referred to as the *affordances of the environment*. These relational properties are the possibilities for action that the environment makes available to an organism. Affordances are the critical relational properties that permit possible couplings between the internal field of the organism and the external field of the environment. Intentions denote a mismatch between the presence of a goal-state attractor (a possible final condition) and the actual state of the environment (the initial condition). Primitive intentions denote mismatches that need to be removed if the organism is to remain fit. By contrast, derivative intentions denote those that the organism chooses to remove for other reasons.

Effectivities are the attractor processes by which the mismatch between the initial and final conditions is eliminated. Hence effectivities map relational properties into relational properties. Consider: Seeing that a chair across the room affords sitting upon; intending to sit on that chair; moving across the room and sitting down. Here we see that intending sets up an attractor dynamics – a mismatch between the current initial condition (i.e., what you are currently doing) and the intended final condition (what you intend to do). We also see that intending assembles and enacts effective means for reaching the intended goal state. Affordances may be viewed as the relevant causal and informational constraints on the intentional behavior; effectivities may be viewed as the informed control processes that accomplish it. More abstractly, effectivities map antecedent affordance descriptions (e.g., affording walking to) into consequent affordance descriptions (e.g., affording sitting upon). Consider next two possible sources of nonstationarity in an ecosystem.

(1) Affordance (goal-state) attractor sets are inherently nonstationary aspects of the external field. As the goal states (represented by the attractors in the environmental field) are created or annihilated, the intersection set will shift (see Figure 20). In other words, a different set of goal states (i.e., the layout of attractors specific to an affordance) is specific to a behavior mode. And as the behavior mode changes, different aspects of the environment become relevant to the organism. For a hungry organism, the objects in the environment will be described in terms of how edible they are, whereas for a sleepy organism, objects in the environment will be described in terms of how well they afford resting.

Note that, in the case of multiple goals, there will be a competition between goal-state (affordance) attractors. Thus, an organism may be both hungry and sleepy, in which case the description of the environment becomes more complex. Each of the goal states may influence behavior, and as we saw earlier, this can lead to complex nonlinearities. Moreover, as was described earlier, all the generic properties of self-organizing systems are equally

important for this account of intentional behavior. Specifically, the organizing of space into fields by attractors, the arising of different modes or qualitative shifts in behavior, the competition between attractors, and the resulting nonlinear behavior all have indispensable roles to play.

(2) Similarly, effectivity attractor sets are inherently nonstationary aspects of the internal field. To take a simple example, as a child grows up, the objects in the environment that have the property of being sit-onable will change. While this particular example has a very slow temporal dynamic, there are many other cases where the change is more abrupt. For instance, as her shape and mass change, a pregnant woman will experience noticeable shifts in her effectivities over a period of months (the principle of similitude: see Kugler, Kelso, & Turvey, 1982; Rosen, 1978). An even more drastic example is the effect that fatigue or injury can have. The action capabilities of an athlete can be noticeably transformed over a very short time span if he/she becomes tired or hurt. Changes in effectivities also play an important role when human operators are required to control complex, technological systems.

To summarize: Affordances are potentially nonstationary, relational, external-field properties that may act as goal-state attractors. They comprise the goal-relevant constraints on intentional behavior. Effectivities are potentially nonstationary, internal-field processes that map the trajectories joining two or more affordance attractors. They comprise the process-relevant constraints on intentional behaviors. Together their coupling forms the ecological field for a given organism at a given time and place. There are two ways in which the geometry of this ecological field can change. As intentions change, the set of affordances relevant to a particular attractor set (i.e., combination of goals) changes. Or, as an organism's effectivities change, the definition of what qualifies as an affordance for that organism changes.

A full understanding of intentional dynamics requires an understanding of how the constraints of this field might change, but still allow stable goal-directed behaviors. This is the open question that stands as the greatest challenge to ecological psychology.

#### *Intentional dynamics: An attractor field at the ecological scale*

What type of image of intentional behavior emerges from the marriage of the dynamics of self-organization and ecological psychology? Here are some highlights.

The intending-perceiving-acting cycle must play a key role in this account since it represents the complex energy-information coupling between the organism and the environment. This coupling can be viewed as the intersection between the set of possible descriptions of the organism and those of the environment. In this intersection, which is nonstationary, reside both the affordance set of relational properties and the set of effectivity mappings among these properties. These represent, respectively, the goal constraints and action constraints on intentional behavior.

The basic theoretical strategy has been to apply the concepts of self-organization to the ecological field. This approach reveals the attractor dynamics that lie at the heart of goal-directed behavior. The attractors in this nonstationary field represent the goal states to be achieved by the organism. These goal states organize the field in much the same way as in the insect-nest example. More specifically, the creation and annihilation of attractors (i.e., goal states) results in a change in the properties of the field, causing a shift to a new mode indicated by a qualitative change in behavior. Within a mode, nonlinear behavior will result if there is a competition between attractors (i.e., if there are multiple goals to be satisfied).

Perhaps the most important characteristic of this view of intentional behavior, however, is the nature of the coupling represented by the ecological field. Just as in the insect-nest example, this is an information-dominated field, rather than a force-dominated field. This is not to say that there are no forces acting within the field. Clearly there are. Indeed, force fields operate within both internal field (e.g., biochemical processes) and the external field (e.g., gravitational forces). The interesting point, however, is that the coupling of these two fields is dominated by information transaction rather than forceful interactions.

Intuitively, intentional behavior is active in that the organism determines how it should move. The organism orients itself with its own energy supply and is not passively pushed around by the force fields in the environment. Successful goal-directed behavior is possible whenever goal-specific information, made available by the environment, can be matched by the control of action exercised by the organism. This dual-information/control field that couples the organism and environment provides the lawful basis for intentional dynamics – although it must be qualified by a graded determinism. Let us explore a little further how a physics with a graded determinism might give rise to intentional systems.

Because complex (biological) systems can store energy internally, they can delay its release from the interior to the exterior field. This results in the emergence of intentionally directed thermodynamic flow processes (e.g., eating cycles, work cycles, sleep cycles, elimination cycles, reproductive cycles, etc.). The delaying of the exterior → interior → exterior energy flow dramatically changes the system's external mode of interaction; no longer is it a "slave" to external-force fields. By delaying these energy flows, the system becomes less reactive in the mechanical sense, but more active in the biological sense. Thus what are mere forces impinging on inanimate systems become stimulation to animate ones. What pushes dead objects to react proportionally may provoke living ones to act disproportionately to the force or stubbornly to resist acting at all. When the reaction is controlled in its disproportionality so as to move the system in some regular fashion not causally preordained, then forceful interactions have the sense of informational transactions.

Delay also permits choice. Having time to be circumspect about its reactions to forces means that the system can give a graded response of its own choosing. Once reaction is not completely determined in conformity with absolute determinism, then internal forces can be

directed to compete actively with external forces. This competition can also become informed and intentionally modulated.

Delay means the mass (or force) dimension essential to kinetic descriptions of inanimate motions becomes less relevant to the dynamical description of animate movements. What remain relevant, however, are the fundamental dimensions of length and time so that kinematics becomes the language for information descriptions. This is how kinematics can come to specify kinetics (Runeson, 1977; Runeson & Frykholm, 1983). These non-mass (e.g., non-force) dominated interactions are properly termed *informational transactions*. They are thus seen to be simply a physical consequence of particles with complex interiors that can actively delay large amounts of energy in relation to external force fields (Kugler & Turvey, 1987). Furthermore, intentional dynamics are the consequence of a system's ability to use this delay tactically to anticipate outcomes to choose among them. More specifically, the capability to delay action permits the system to become informed of final-state possibilities, to select one as a goal-state, and then to reinitialize the attractor field under its control so as to achieve that goal state. This is what is meant by saying intention sets up a goal-state attractor dynamics.

A related and equally important characteristic of self-organizing systems is that they actively partition the information field into a coupling of internal and external fields. Because these fields are open, they become nonstationary; thus the intersection set coupling these two fields is continuously changing. Traditionally, this intersection has been modeled as a static independent set that acts as a mediator between the other two sets, resulting in the creation of many paradoxes (e.g., the mind-body problem). In contrast, the ecological, or dual-field, approach adopted here realizes the importance of the dynamic coupling between the internal and external fields being direct (nonmediating) that results in a common relational information field. All descriptions of the two fields, other than the common set, lead to problems of dualism and incommensurability.

An implication of the graded-determinism argument is that holonomy (strong lawfulness) holds with respect to information, not with respect to action. That is, even though there is a lawful relationship in the information field specifying what the organism should do to satisfy an intention, the organism need not obey this information. A property that distinguishes intentional systems from causal systems is that they can go against the gradients specified by the information field. If the organism is tired and information is available that can lawfully guide the organism to a resting state, the organism can still decide to follow another path. The analog in the insect example would be an insect that chose not to follow the gradient to the location where an arch was being constructed, even though the information was available for it to do so. Regardless of the path that is chosen, however, the proposed account of intentional behavior suggests that there will be information available to guide behavior.

The primacy of perception implies that the regularity applies necessarily on the perceptual side because informa-

tion arises lawfully, but only contingently on the action side, which may be governed by rule or caprice. Perhaps, on the action side, the system must learn how to behave lawfully if its intended goals are to be achieved. The existence of these or other lawful (i.e., holonomic) relationships that determine goal-directed behavior remains an open question.

*On the origins of semantic predicates: A realist approach to symbol functions*

Where do symbols come from? How do the symbol functions of living languages pick out the objects of reference (states of affairs in the environment) whose contents give meaning to our objects of intention (our beliefs, expectations, desires, fears, plans, and so forth)? What is the original source of the dynamics of symbol systems that syntactical analyses of living languages abstract as grammatical rules? How do phonology and orthography get coupled so that we can hear what we see and see what we hear? These are profound issues upon which no psychological theory can remain mute. Ecological psychology, no less than information-processing approaches, must discover a portal through which symbol dynamics may enter into intentional dynamics.

For every primitive or derived intention pursued by an organism there corresponds directly or indirectly specified information about the goal that is the content of the act. The affordance whose realization is intended provides the reference for the effectivity by which the act is executed. Affordances and their associated effectivities comprise the intersection set between the organism and the environment. Primitive symbol functions are defined on this intersection set in the following manner: a primitive symbol function relates an external-field state, called the symbol vehicle, that is specific to an affordance-goal gradient, to an interior-field state, called the symbol topic, that is specific to the dual effectivity-force gradient. This affordance-effectivity duality is called the ground of the symbol function. The symbol function may be inverted in such a way that the roles of topics and vehicles are reversed. For instance, on one occasion, a baby may perceive a nipple brushing its cheek (affordance vehicle) as something that is suckable (ground), and make head orienting and sucking movements intending to nurse (effectivity topic), while on another occasion it may make sucking movements (effectivity topic) and turn its head in a vain search for a nipple to be sucked (affordance topic).

More precisely, the vehicle or topic is informationally or functionally specific, respectively, to the attractor defining the corresponding affordance or effectivity gradient, rather than to the gradient itself, which may be ignored. There is a mapping from a continuous field description, defined by a complex layout of gradient basins and attractors, to a discrete set of attractors (i.e., symbols). A mapping that selectively eliminates some detailed information about its domain is technically referred to as a forgetful functor (i.e., a homomorphic mapping), in contrast to a faithful functor – a mapping that preserves all the detailed information about its domain (i.e., an isomorphic map-

ping). For instance, on a still later occasion, the baby may make abbreviated sucking movements (a forgetful force functor) to approximate the sounds of nursing in order to get fed, and, in doing so, recall the softness of the nipple against its cheek (a forgetful informational functor); and follow this with appropriate nipple-searching movements of the head (a faithful force functor). This example illustrates a sequence of derived intentions of different degrees of abstraction, as determined by the graded forgetfulness of the associated functor. Thus, because of the selective elimination of detail, symbol functions in general provide a way in which specific states of an organism and specific states of its environment may remain coordinated in the absence of forceful or informational gradients. The following conclusions can be drawn from these hypotheses:

(1) By preserving the pairing of dual attractors (affordance, effectivity), which in the appropriate context act to organize informational and forceful gradients, the symbol function retains, by means of forgetful functors, some abstract, discrete version of the original dynamics. This degraded dynamic, which at limit only preserves the ground (the affordance/effectivity duality), acts as a set of virtual information gradients or virtual force gradients. In this way, symbol functions provide socially available vehicles that preserve selective information about goals in the absence of overt intending, on the one hand, and that sustain intending in the absence of goal-specific information, on the other hand.

(2) Symbols derive their synonymy from shared allegiance to affordances, while their common syntactic function derives from how they are shared by a given effectivity. Consequently, symbol systems have a dynamic for adumbrating, reflecting, and recording the repartitioning of the intersection set. Although this symbolic dynamic must be fast enough to shadow the dynamical changes in the intersection set, its (syntactical) rules must be historically stationary as compared to the ongoing dynamics of the intersection set – otherwise meaning would be too unstable to be used or to be useful. Put differently, symbol dynamics provide a way for physical traces to become records, and for records to be used hereditarily or memorially as support for the persisting knowledge of the organism's naturally selected or learned transactions with the environment, respectively.

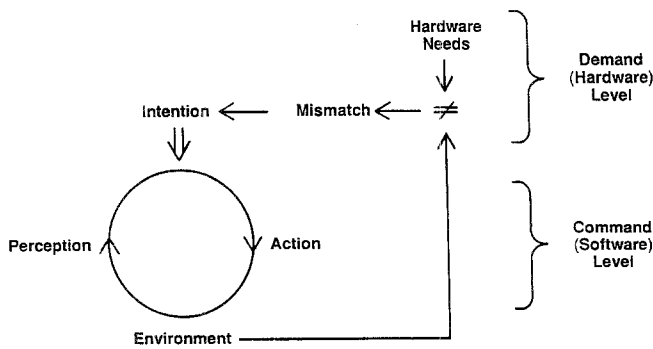
Anyone who doubts that symbols have a dynamic that defines virtual attractor gradients has never attempted to follow verbal or written directions to a destination in a strange city; or to cook or do lab exercises by following a written or remembered recipe; or tried to put together an intricate Christmas toy from its packing instructions; or attempted to replicate an experiment; or to program a computer. In each case the intentional object (the desire to follow the instructions) had better be attracted to the intended object of reference – a virtual equilibrium point in an informational defined workspace – or the exercise is a failure. In this sense, languages as systems of symbol functions (forgetful functors operating as attractors) are social tools for building virtual gradients whose intentional dynamics might be shared with others, while guiding us over nonholonomic regions of our private state space.

*Making symbols matter and need: Humanistic, rather than mechanistic, physicalism*

Conventional interpretations of symbolic dynamics asks: To what arbitrary pre-existing object is the symbol function attributed? A physical interpretation of symbol origins asks instead: By what evolutionary principles do symbol functions fashion their material instantiations? The conventional view assumes that symbol functions are rule governed, and hence nonholonomic from their inception – mere conventional ascriptions through and through – which accrue stable meaning only by prescriptive use. Their dynamics are syntactic manipulations under semantic contextual constraints, which are not necessarily truth functional or dependent on real-world contexts. Under this view, sentences may be sentences even if untrue or anomalous; but they may not be sentences if ungrammatical.

*Requirement of a materialization process for symbols.* By contrast, a naturalistic view of symbol origins identifies the evolutionary design of primitive symbols with holonomically constrained, self-organizing processes that develop in stages. In the first stage, the self-organizing process arises from holonomic constraints (e.g., the insect randomly dropping pheromone-rich material); in the second stage this process gives rise to nonholonomic constraints (e.g., concentrated regions of pheromones that create diffusion gradients); in the third stage, these nonholonomic constraints (pheromone sources) become materially instantiated and frozen in spatial degrees of freedom (e.g., as dome-bearing pillars); and in the fourth and final stage, these constraints may be used by the system to rectify nonholonomic regions of its state space by leveling the sources and sinks (i.e., used as a roof over which the holonomic, autocatalytic process of stage 1 is reinitiated and the process repeats itself). In this process, a set of nonholonomic constraints emerges as a materially instantiated record of the critical points generated in the holonomically constrained pheromone diffusion field. The material record is a subspace description of the pheromone field. We view these records as primitive symbols associated with less detailed descriptions of the pheromone field. Fundamental to all natural symbol-manipulating systems is the requirement of a process that materially instantiates a less detailed description of a system in physical degrees of freedom.

*Requirements of wetware (hardware) needs that are served by ideas and intentions (software).* Where the hardware systems serve their programs under the conventional view of symbol dynamics, the programs serve the hardware under the physical interpretation. The slave-master relationship is inverted because self-organizing systems are self-writing and self-reading; conventional systems (computers) have programs written for them to be read by someone other than the system whose needs it fulfils. Only when programs serve the needs of the system that writes and reads them will symbol dynamics be understood. The programs causally drive the states of the computer rather than intentionally serving them. Hence computer software has no primitive needs emerging from its supporting hardware



**Fig. 21.** The coupling of demand (hardware) level and command (software) level (see text for description).

and subsequently no corresponding primitive intentions arise that serve them. A genetic program (software) is read by a system whose wetware (hardware) needs it to remain viable and adaptive. In biological systems the wetware places a continual set of functional demands on the system's mental states (ideas and intentions) for its viability and adaptability. The continual flux of foodstuffs into the system in high potential form and out of the system in low potential form (heat and waste) results in the formation of intermediate work cycles. These work cycles, in turn, are causally responsible for the continual maintenance of the input of foodstuffs, requirements of the First Law of Thermodynamics, and outputs of waste, requirements of the Second Law of Thermodynamics. As energy begins to be stored internally in metabolic reservoirs, time delays develop between the inflow of energy and the output of intermediate work cycles. These time delays result in the system's input-output needs becoming temporally separated (e.g., as the collection of foodstuffs becomes temporally divorced from the utilization of the foodstuffs). The concept of primitive intention, as used here, is linked to the functional requirements associated with these time delays. In this context, primitive intentions are born out of the needs of the hardware as dictated by the First and Second Laws. The actions of these intentions can become more remotely related to the demands of the First and Second Laws as the amount of time needed to satisfy the requirements of these needs is reduced through technological and agricultural efficiency.

*Emergence of intention out of hardware needs rather than software complexity.* The design of an intentional system requires the establishment of a linkage between the hardware needs and the software demands of a system. Traditionally programs provide the syntax for linking or sequencing commands that satisfy the demands of the program designer. The demands cannot arise out of the syntactic (command) level. Rather, the demands constrain and motivate the syntactic level. In this view, the demand and command levels are distinct. Intention arises out of the demand level as the expression of need. There are no self-demanding programs. The assumption that commands (intentions) arise out of the syntax at the command level leads to well-recognized problems of self-referential paradox, codability, and truth. Under this view, intention emerges out of the complexity of the software as an epiphe-

nomenon at the command level. By contrast, under the ecological view, intention emerges as a phenomenon at the demand level out of the needs of the hardware. The coupling together of the command (software) and demand (hardware) levels is realized in the form of a perception-action cycle. The perceptual system, as a command level, places constraints on the action system at a demand level. Primitive needs emerge out of the nonstationary character of the hardware (e.g., needs to satisfy hunger, sleep, reproduction, etc.). The needs, in turn, demand attention that guides action through the realization of an intention.

The relationships between the demand and command levels (or alternatively, between hardware and software) are represented in Figure 21. The command level corresponds to the perception-action cycle described earlier. Perception guides the assembly of an effectivity for satisfying the affordance goal, and action in turn guides perception to the desired goal state. This reciprocal coupling of perception and action explains how an information field can lawfully provide an informed basis for goal-directed behavior. However, the selection of the intention (i.e., a goal state) does not arise at this level.

The origin of intentions arises at the demand level. Owing to the nonstationarity of the hardware, primitive needs arise autonomously as a function of constraint dictated by the first and second laws. These needs correspond to the set of primitive modes described earlier. A given primitive need leads to a tension that can be viewed as a mismatch between the current state of affairs and the current needs of the hardware. Attention is required to pick up on this mismatch, leading to the selection of an intention specific to the mode that will result in the satisfaction of the current need. Once selected, this intention serves as a basis for setting up the perception-action cycle described above. In this way, the command and demand levels become coupled.

Several points about this coupling are worthwhile emphasizing. First, the nonstationarity originates in the hardware at the demand level. It is this nonstationarity that leads to the creation of intentions. Second, the actual execution of goal-directed behavior is governed at the command level.

Thus, the demand level selects and sustains the affordance-effectivity relationship, and the latter, in turn, guides behavior. This relationship, illustrated in Figure 21, can be summarized as follows:

*nonstationarity of hardware* → *primitive need* → *mismatch* → *intention* → *perception* → *action cycle*

In this model the referent against which the mismatch is defined emerges as a property intrinsic to hardware level. It is not a referent defined at the syntactical or command level; rather it is assumed and used by the command level.

Several important properties of this account of intentional behavior distinguish it from purely symbolic accounts. For one, the symbolic level is coupled with the dynamic level governing interaction with the environment. In this way, the symbol-reference problem that plagues traditional approaches is avoided. Furthermore, the problem of the origin of intentions is also addressed. It is viewed as a mismatch between the current state of the

environment and the changing needs of a nonstationary hardware. Such an explanation overcomes the regress problem associated with purely symbolic accounts (e.g., “Who designs the program?”). We note that this limitation of symbolic approaches stems from the assumption that the hardware and software can be decoupled. Breaking with this widely accepted assumption allows us to acknowledge the nonstationarity of the hardware (i.e., wetware) of the human organism, and at the same time provides a hypothesis regarding the origin of primitive intentions.

## Conclusion

This paper has taken a few steps toward providing a better understanding of intentional behavior. One important step was the discussion of germ determinacy, which may be used to express several central concepts of ecological psychology that have proven difficult to formalize. In this way Gibson’s principle of animal (effectivity structure) and environment (affordance structure) mutuality (in the sense of a mathematical duality) might ultimately find expression.

Other important steps toward modeling systems with intentional dynamics were suggested by consideration of generic mechanisms by which open systems self-organize under energy interactions, on the one hand, and through information transactions, on the other. The ecological field, which couples the internal field of the organism and the external field of the environment, was proposed as providing the necessary information to guide intentional behavior lawfully. It was shown how the organization of this nonstationary field (i.e., the organism-environment intersection set) depends upon changes in the number and layout of the attractors within it. These attractors are dually specified by the affordance properties of the environment and the effectivity functions of the organism that realize them.

It was also suggested that the nonstationarity of this set (the change in number, layout, and/or intensity of goal-attractors with the associated changes in germs of trajectories) may permit the evolution of derived intentions in the guise of a more slowly changing (quasi-stationary) symbol dynamics. Here symbol dynamics stands to intentional dynamics as a higher-order, more abstract analogue similar to the way kinematics stands to mechanics. A theory of intentional dynamics should contribute to our understanding of how living systems realize their primitive intentions (evolutionarily determined and ecologically learned needs and expectations). Analogously, a corollary theory of symbol dynamics should contribute to our understanding of how living systems realize their derived intentions (wishes, plans, ambitions) – those intentions that do not arise automatically as modes in a recurring cycle – intentions that may be interpolated between modes, but whose gratification must therefore often be postponed and only resumed after many lengthy interruptions (i.e., after sleeping, eating, escaping danger, finding shelter, etc.).

It was further argued that there are unique configurations of goal-state attractors from whose dynamic interplay cycles of qualitative behavioral modes may lawfully emerge. Thus, the principles of self-organization provide a holonomically constrained account of intentional behavior

that reveals how organisms can become, and remain, lawfully informed in the pursuit of their goals. Complemented by symbolic dynamics, the generalized theory should provide a means to understand how intentions maintain the system on its goal trajectory, even when it must cross regions of nonholonomy where laws at a given level of analysis do not strictly apply or environmental sources of controlling information are obscured or absent.

If successful, a theory grounded on the premises proposed here would take us one step closer to solving the puzzle posed by Gibson (1979) when he asked: How is it that “behavior is regular without being regulated?” (p. 225) in a complex, dynamic, and unpredictable environment.

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