

COGNITION AND THE SYMBOLIC PROCESSES:

Applied and Ecological Perspectives

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The Role of Attractors in the Self-organization of Intentional Systems

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INTRODUCTION

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 fields of artificial intelligence and robotics. Motivational and cognitive psychology have each perennially addressed certain aspects of the problem without appreciably reducing its problematical core. In spite of the generous efforts of all of these disciplines, the role of intention in guiding self-motivated systems still remains shrouded in mystery and haunted by the recursive presence of unexorcised ghosts.

The purpose of this chapter is to consider some of the physical and modeling prerequisites for an informational basis for intentional dynamics. 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.

The chapter begins by comparing and contrasting the influence of equilibrium points, or attractors, in physically isolated and open systems. Equilibrium points, or attractors, are singularity points. The set of attractors in a system, however, can become nonstationary as competitions develop locally among individual attractors. The first section focuses on the identification of the mechanism driving the nonstationarity of the attractor set. This mechanism provides a generic construct for modeling self-organization within the context of both inanimate and animate systems. In the following section, a biological example of self-organization is presented to show how the mechanism of self-organization can be instantiated in an animate context. Particular attention is paid to the role of attractors in organizing an informational field for the biological system, thereby providing an *information*-based organizing mechanism for behavior—as opposed to the *force*-based mechanism exemplified by inanimate systems. A discussion of some of the theoretical issues associated with goal-directed behavior is undertaken next to provide the necessary context for the ensuing section on the self-organization of intentional systems. In that section, the generic properties of self-organization are integrated with the problems posed by goal-directed behavior, thereby suggesting how an information-based, ecological approach to intentional dynamics can be pursued.

GENERIC CONDITIONS THAT CREATE AND ANNIHILATE EQUILIBRIUM POINTS

Whether it be in the domain of 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. Knowledge 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 for doing so, or alternatively, 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 in time 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 toward 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 or a chaotic regime).

In a mathematical system, the area of the state space toward which the system converges as time tends towards infinity (whether it be a limit point, 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 which 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.

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. 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 particle to the flat surface. This friction defines a force threshold below which there is no motion of the particle. Fig. 23.1 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 only reveal the part of the magnetic field that is above the frictional threshold. This part defines the force contribution that scales to the motion of the particle in the field.

Fig. 23.1a 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. Fig. 23.1b 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 midpoint between the two attractors, it will remain there since the force fields in this location are not strong enough to move the

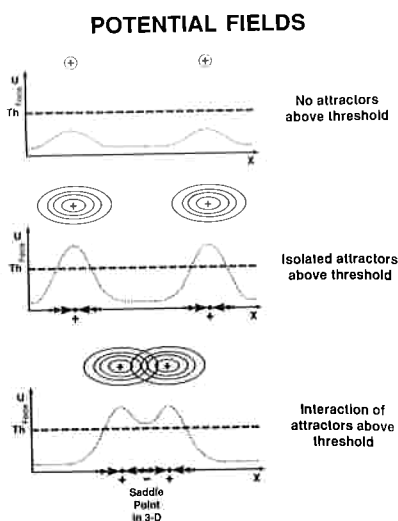


FIG. 23.1. Topological characteristics of magnetic gradient fields.

particle. In the configuration shown in Fig. 23.1b, 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, it either experiences the attractive force of one of the attractors, or it experiences no significant force at all.

Finally, in Fig. 23.1c, 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" in the force field 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 dynamic system. A change in the attractor layout will result in a qualitative shift to a different behavior mode. In the example given, 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, however, 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). For reasons to be discussed, only systems that are open to energy, matter, and information flows can exhibit this type of behavior.

Maximum Entropy vs. Self-organization

In an isolated system (i.e., one that is 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.¹ 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.* The 19th-century German physicist Rudolf Clausius observed that *the entropy of the universe will tend to a maximum value* (Atkins, 1984). This implies that the intrinsic evolutionary tendency of the universe is towards states of increasing disorder, ultimately converging onto a state of equilibrium where disorder is maximum. Once at equilibrium, all future possibilities of change in order 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 locally seize control of the dynamic from the global influence of maximum entropy and evolve the system toward states of greater order, in 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.

¹Entropy 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.

Irreversible Processes, Disorder, and Isolated Systems

The Second Law is one of the laws defining observations at the macroscopic scale of nature. The law identifies why a drop of ink tends to spread out in a glass of water instead of remaining as 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 of entropy over time (i.e., an increase in complexity, organization, or order). In these regions, nonstationary, irreversible processes can develop that selectively organize or mix the macroscopic properties of matter (e.g., temperature, pressure, chemical concentration) 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. Let us consider the principles of the "new physics" that have allowed us to understand these processes.

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 the emergence of structure 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 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 pumping 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 by-product of the Second Law's dissipative processes.² The system exhibited a natural tendency to self-organize. In recognition of the central role played by dissipative processes in self-organization, Prigogine termed these open systems *dissipative structures*. In 1977, Prigogine was awarded the Nobel Prize in chemistry for his work relating dissipative processes to self-organization in open systems.

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 defined by the state of maximum entropy (minimum order). As time tends toward 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 introducing nonlinear force terms (e.g., quadratic or higher order) into the original state equation. According to the

²A 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 toward infinity, the energy in an isolated system will dissipate from macro modes to micro modes, resulting in an increase in entropy.

new equation, the state of maximum entropy identifies an equilibrium point in state space that operates when the system is 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 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 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 is composed of a coupling between two processes that generate opposing tendencies, thereby resulting in the creation and/or annihilation of equilibrium points. 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 dissipative process, then the local maximum entropy attractor will have the most 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.

Later we shall use the concepts of escapement and dissipation to describe systems with attractors that may qualify as goals. Let us pause to consolidate the concepts needed to address the question of how systems may exhibit intentional dynamics without violating the physically lawful accounts of open systems.

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 Fig. 23.2. 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 kinetic energy. Due to 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 vibra-

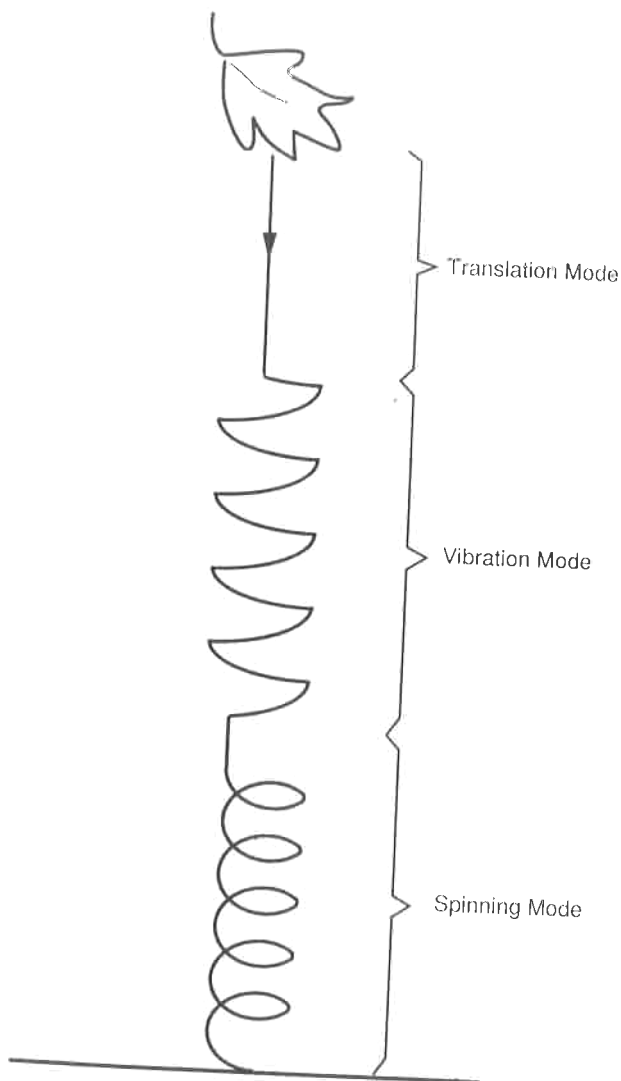


FIG. 23.2. Dynamic modes (translation, vibration, and spinning) of a falling leaf.

tion. This mode consumes 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 simple example, the fundamental process by which an open system self-organizes can be abstracted.

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's dynamic 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 further from equilibrium.

As the leaf example shows, 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. 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, for instance, Carreri, 1984; Casti, 1989; Davies, 1989; Haken, 1988; Nicolis & Prigogine, 1989; Yates, 1987).

So far, we have discussed the role of attractors in organizing the behavior of inanimate physical systems. Our aim in this chapter is to characterize their role in the self-organization of intentional systems. Note that the application of attractor dynamics to intentional systems is meant as more than a casual analogy; rather we take it as a working hypothesis about the nature of the mechanism for understanding goal-directed behavior in biological systems. In the next section, we provide an example of self-organization of an ensemble of biological subsystems (insects) that are mutually linked through a low-energy, pheromone field coupling. The model illustrates an open system that is as informationally driven as it is energy-driven. It is a system that is not only thermodynamic but *epistemic* as well. That is, its thermodynamically driven activities are informationally controlled toward an evolutionarily selected goal—the self-assembly of a large-scale nest for millions of insects. To achieve this *naturally selected primitive intention*, the system begins in a state of low order and then, guided by the principles of self-organization, subsequently evolves recursively into states of successively greater order as new equilibrium points emerge and compete with existing equilibrium points. Thus 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 systems.

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 more than 300 years. This feat is made even more remarkable by the fact that the termites work independently of each other. The insects' 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. The pattern is specified by the unique number and layout of attractors in the pheromone field that is 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. Because of the field dynamics they impose, this ensemble of attractors comprises a global *organizing mechanism* for local trajectories. As with 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, the pattern in the field 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 therefore a function of the creation and/or annihilation of one or more attractors.

In the following section, the various changes that take place in the field governing the insects' behavior as a function of changes in the layout of attractors in that space will be described.

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 relative to the global structure of the pheromone field.

The diffusion field spreads out in accordance with Fick's law³, which 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 ($grad = 0$ for the entire field) 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 insects' 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. (The analogy to be drawn here is to the sliding friction that has to be overcome if a particle is to move toward a magnetic pole.) Once insects enter an activation region they follow paths mapping the *streamlines*⁴ 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 buildup of new waste material in the insect.

³Fick's law states that the rate of transport is linearly proportional to density.

⁴A streamline is a line of flow which is everywhere orthogonal to the isopotential contours of a field. In the case of a gradient field, the streamline defines a path of steepest gradient.

The role of perceptual thresholds in the insect system is similar in some respects to the role of the force threshold in the magnetic field example that was illustrated earlier in Fig. 23.1. Just as the force field may be too weak to move a particle (Fig. 23.1a), the pheromone concentration may be too weak for the insect to detect. Similar to the case in Fig. 23.1b, if the pheromone concentrations are far apart, then they will not interact with each other in regions above threshold. Finally, as we shall see, the case of two attractors that are close enough that their interaction is above threshold will, just as in Fig. 23.1c, result in a competition that leads to nonlinear behavior. Next, we describe the four modes exhibited during the next-building process.

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 patterns (i.e., no local equilibrium points organize the field dynamic). 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's 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 Fig. 23.3). 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 Fig. 23.4). The pillar is constructed at the location of the equilibrium point, with only the top of the pillar remaining active.

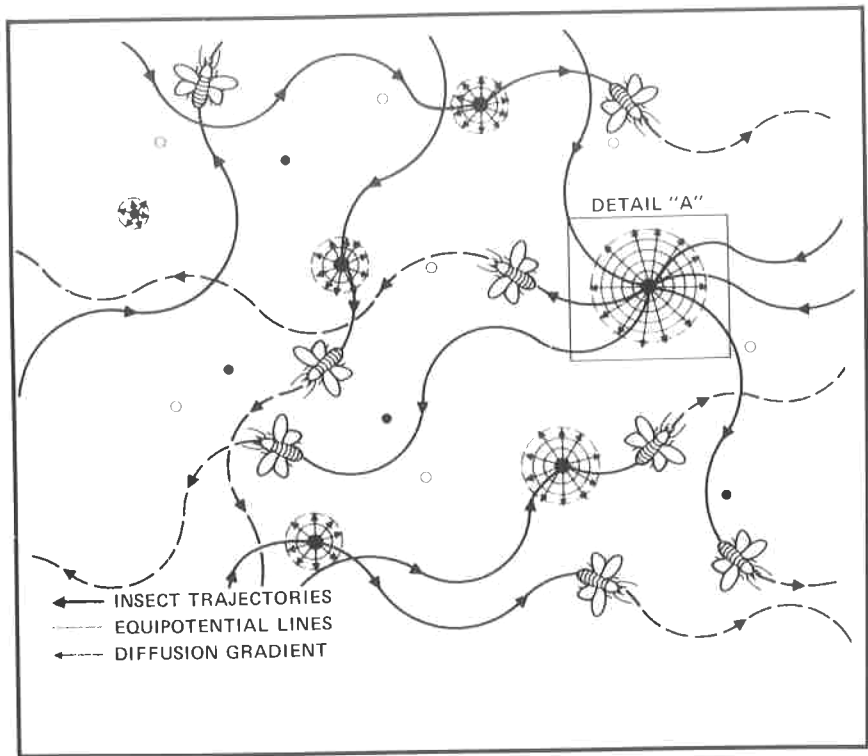


FIG. 23.3. Development of preferred sites. The development of a preferred site marks a sudden transition in the correlational state of the insect population. As the size and number of preferred sites increases correlations begin to develop among the insects' external coordinates of motion. The insect behavior is no longer at equilibrium (independent of one another), it evolves into nonequilibrium states exhibiting increased correlation (adapted from Kugler & Turvey, 1987).

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 construction phase, all pheromone gradients above the insect's perceptual threshold contain only one equilibrium point. In these localized regions pheromone flows relates *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

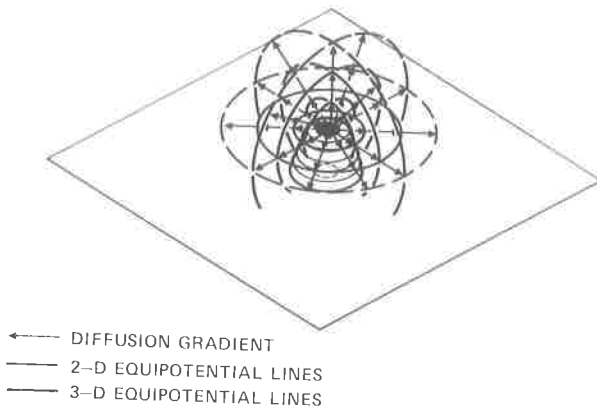


FIG. 23.4. Building a pillar (adapted from Kugler & Turvey, 1987).

to overlap (recall case *c* in the magnetic field example). *Saddlepoints* organize the interface boundary separating the two gradient fields. The saddlepoint is a fixed point property that defines a common solution that relates the two local gradient fields. The saddlepoint thus forms a set of field constraints that are used by the insects in the construction of an arch (see Fig. 23.5).

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 that is 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 Figs. 23.6 and 23.7).

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 constraints of both pillar basins. Thus, the saddlepoint is a higher-order attractor defining a symmetry that is invariant over the 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 relative to two pillars.

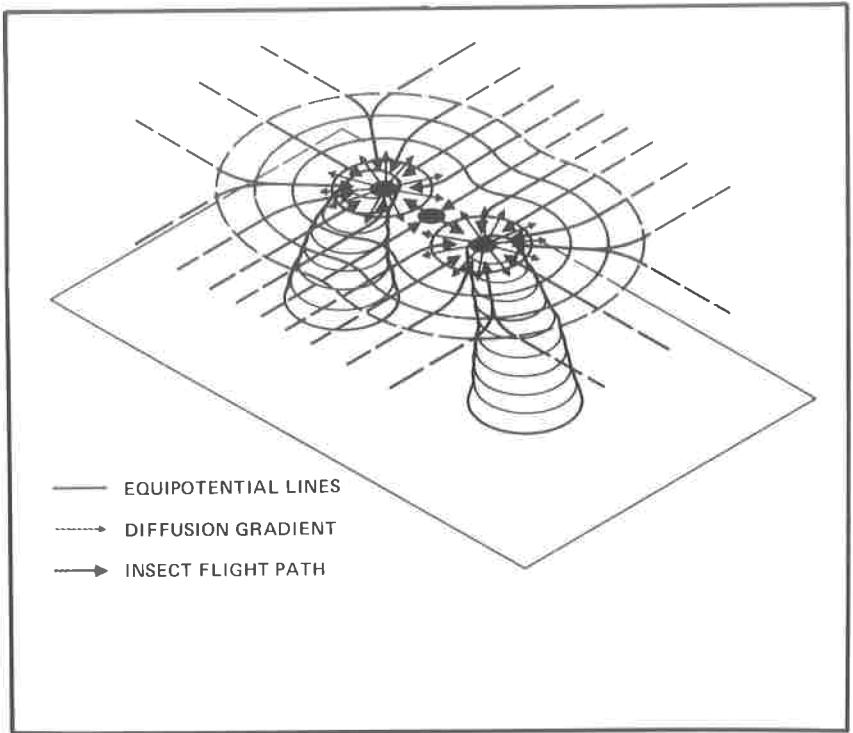


FIG. 23.5. Building an arch. The emergence of the saddlepoint further displaces the system from equilibrium. The organizing influence of the saddlepoint extends the insect correlations to a region defined over the two pillars (adapted from Kugler & Turvey, 1987).

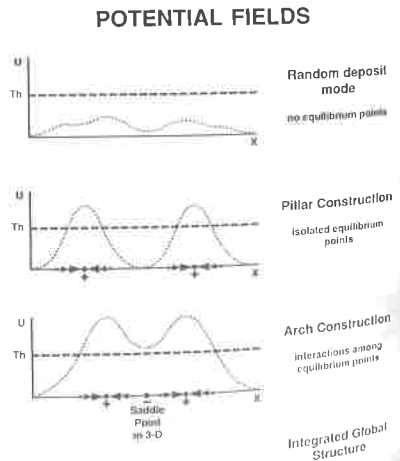
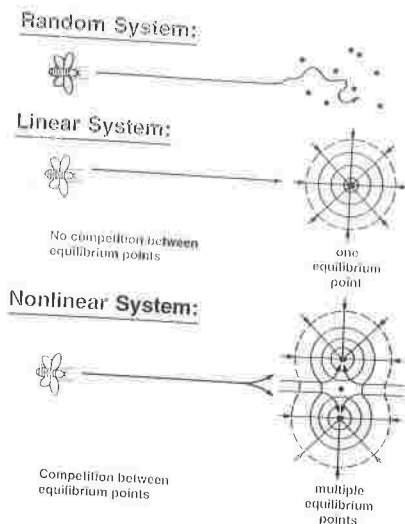


FIG. 23.6. Comparison of the potential fields for the random flight mode, pillar-building mode, and arch-building mode. Compare with Fig. 23.1

FIG. 23.7. 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).



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 two pillar equilibrium points with the emergence of a single equilibrium point at the top of the arch (see Fig. 23.8). 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, provide new constraints which coordinate the construction of a dome (see Figs. 23.9 and 23.10).

Upon completion of the dome, the far-from-equilibrium condition is annihilated; this results in a return to the equilibrium mode. A new construction cycle then begins, starting with the random deposit phase on the surface of the dome. The system begins another cycle through the sequence of construction modes (Fig. 23.11): random deposit \rightarrow pillar construction \rightarrow arch construction \rightarrow dome construction \rightarrow random deposits, and so on.

There are several aspects of this example we wish to emphasize. First of all, 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 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 Fig. 23.12). The circular linking of the

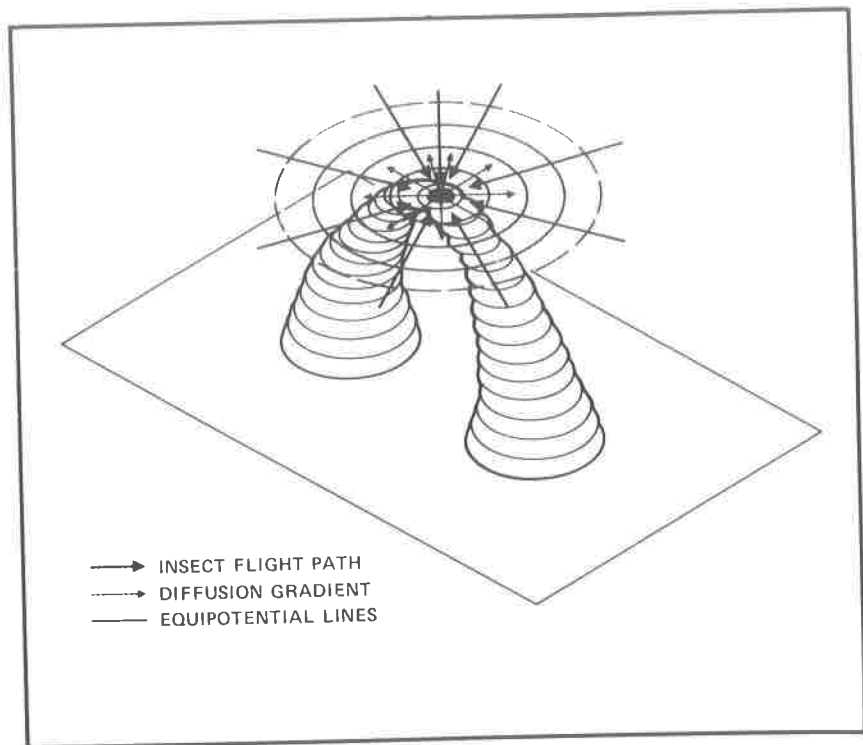


FIG. 23.8. Completion of the arch and annihilation of the saddlepoint (adapted from Kugler & Turvey, 1987).

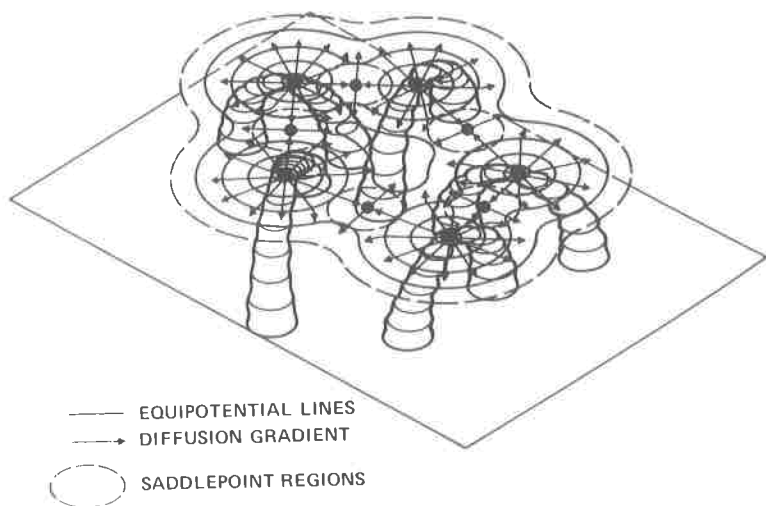


FIG. 23.9. Emergent saddlepoints are used to build a dome (adapted from Kugler & Turvey, 1987).

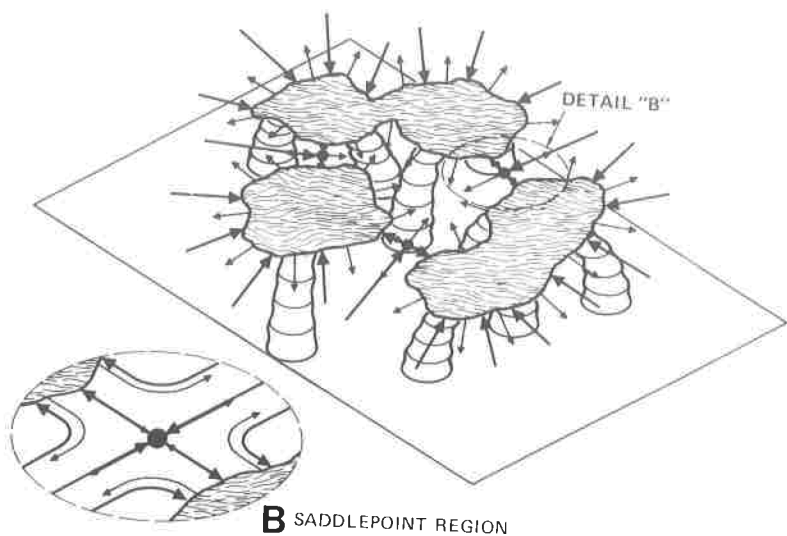


FIG. 23.10. Development of a dome (adapted from Kugler & Turvey, 1987).

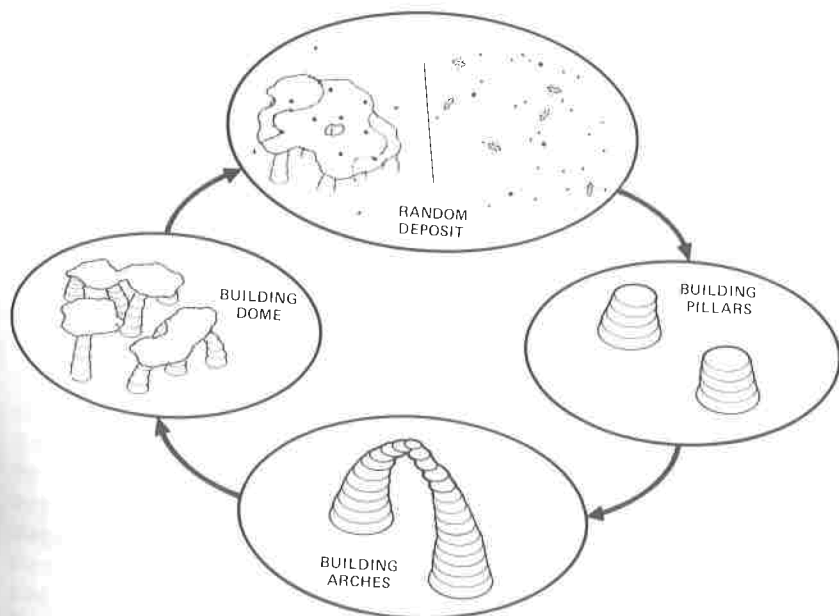


FIG. 23.11. Circular ring of building phases. Each phase is dominated by a small set of critical (degenerate) states that organizes the chemical flow fields. These flow portraits provide the controls constraints that orient the insect's motion (adapted from Kugler & Turvey, 1987).

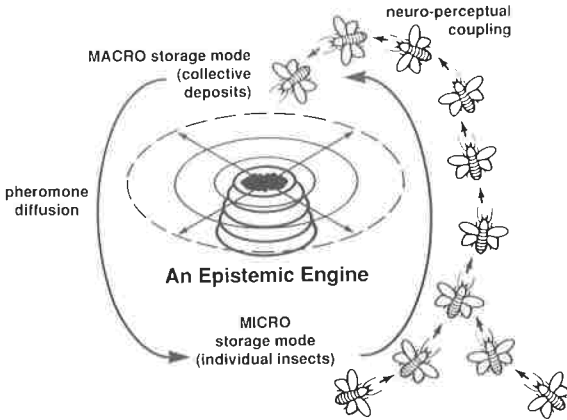


FIG. 23.12. Self-reading, self-writing, self-organizing information system (adapted from Kugler & Turvey, 1987).

replenishing and dissipation of pheromones through a perceptual 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 energy flows, we have a closed thermodynamic-epistemic engine cycle (Fig. 23.13; see Kugler & Shaw, 1990): force field (muscular activity)→flow field (pheromone control constraints)→force field

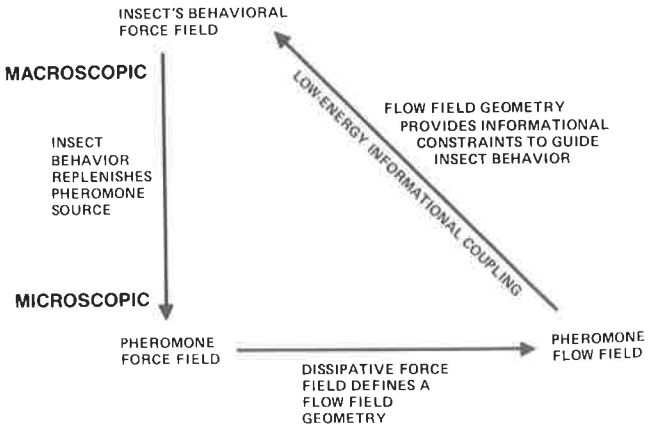
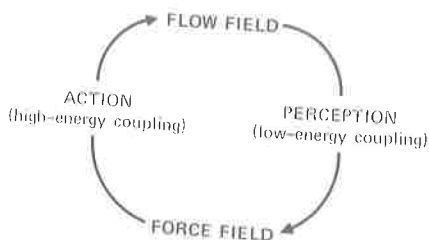


FIG. 23.13. The individual insects define micro storage modes for the pheromone. The active deposit site on the pillar defines a macro storage mode. The insect's transport of the pheromone to the top of the pillars is an escapement process (micro→macro transport) and the diffusion process that distributes the pheromone from the top of the pillar to a uniform distribution is a dissipative process (macro→micro process).

FIG. 23.14. Perception action cycle. A circular causality of self-assembled flows and forces (adapted from Kugler & Turvey, 1987).



(muscular activity)→flow field (pheromone control constraints), and so on. Alternatively, the engine cycle can be described as an action→perception→action→... cycle (compare the cycle depicted in Fig. 23.14 with the cycles depicted in Figs. 23.12 and 23.13).

Finally, it is important to emphasize that the nest-building system is a thermodynamically open system. As pointed out in the previous section, self-organization is possible only when a system is open to the flow of energy and mass. In any self-organization process, it is the *thermodynamic pump* which plays the critical escapement role, adding a higher grade of energy to the system (local regions of high pheromone concentration). 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, as an epistemic engine, information is also "pumped" into the system. An understanding of how the informational linkage arises and works in completing this circularly causal system is a strong challenge to any cognitive psychology. Let us consider this informational linkage more closely.

Primacy of Informational Linkages

Like the falling leaf, the insect nest example provides an effective illustration of the properties of self-organization that were discussed in the previous section. However, it also possesses an important property which distinguishes it from both the leaf and 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 it 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, however, 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 (see Reed & Jones, 1982; Kugler, Turvey, Carello, & Shaw, 1985). Gibson's methodology focused on the physical and functional significance of nonforce interactions. By focusing on nonforce field descriptions, a natural transition can be made from the physical theory of self-organization to a theory of self-organizing information systems⁵.

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

In this section, several modeling issues associated with goal-directed behavior will be addressed, including different types of teleological mechanisms, the role of the perceiving-acting cycle, and the primacy of perception. This will serve as background for the following section, where we will illustrate how the concepts of self-organization, attractors, and the lawful determination of information can be brought to bear on the problems described here.

An Inventory of Teleological Mechanisms

Teleological determinism is the philosophical view which 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 (Braithwaite, 1953; Russel, 1945; Taylor, 1966; and especially Woodfield, 1976). Such a thesis can be held only if one repudiates the principle of state determinacy.

State-determinacy. In midcentury, cybernetic approaches attempted a scientific reformulation of the problem of intentional dynamics by identifying goal-determinacy in terms of state-determinacy (Ashby 1952, 1956; Rosenblueth,

⁵For extended discussions on the topic of self-organizing information systems, see Kugler, Kelso & Turvey, 1980, 1982; Kugler 1986, 1988; Kugler & Turvey, 1987, 1988; Kugler & Shaw, 1990.

Wiener, & Bigelow, 1946; 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 set-points 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. For instance, 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 wisely 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; or as Aristotle might say, its formal cause. 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, analytical 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 analytical projection in the *temporally backward* direction as a formal description for corollary explanatory laws of action mechanics. Unfortunately, as Weir points out, 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 con-

vinced 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). This field was so christened because its mathematical power derives from the calculus of variations—a technique by which laws of mechanics may be rendered in integral form rather than in differential form as is usually the case. 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 that point which 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 them that which is minimal. On the assumption that a path is a minimal curve just in case it is the intended goal-path, many theorists (e.g., Maupertuis) 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 (see, for instance, Mach, 1974/1893, p. 550; Poincaré, 1952/1905, p. 128). 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 (1985) 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 that goals might constrain actions. For this we need to replace the notion of an analytical 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 analytical 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 which expresses nondeterministically the distinctive shapes that paths may assume.

Weir proposes that *goal-determinacy* is mathematically identical to *germ-determinacy*, a concept which 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 analytical and nonanalytical mappings from past states to goal-states.

In summary, Weir argues that goal-directed behavior is nonanalytical, bifurcatory behavior requiring germ-determinacy 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 global 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. (Exactly how goals may informationally specify constraints on behavior, which may be followed if the organism intends to do so, has been addressed in detail and, to some degree, made mathematically explicit in Kugler & Turvey, 1987; Shaw & Kinsella-Shaw, 1988; Shaw, Kugler, & Kinsella-Shaw, 1990; Kugler & Shaw, 1990).

This brief summary prepares us to appreciate the full significance of Weir's (1985) solution to the mechanism of teleological determinism. According to him, goal-directed behavior "... necessarily involves explaining the behaviour that occurs by reference to some behaviour being perceived to bring about the goal. And if behaviour 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 the 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 relative to the temporally forward flow of action paths. (A defense of the plausibility of this suggestion has been given by 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 systems 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. Bear in mind that just as we can take an ecological approach to perception and action, so we can also to cognition, as we attempt to show next.

Intending Systems as Opposed to Systems Merely Having Intentions

In the magnetic field example we saw what it means for an isolated system's behavior to be governed by attractors. But there was no capacity for self-organization. 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. Our analysis of self-organizing systems was extended once more by the termite nest-building example. Here 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, for example, 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. Intention is identified with an operator that selects, from among all possible final states (or structures)⁶ of a system, a

⁶The set of final states need not be points in space-time. Instead, they might consist of a set of observable "tendencies" that are defined along some fitness criteria. For example, a final state might be defined by the system achieving a path that *tends* to improve the performance maximally along the fitness metric. The set of possible final states would then consist of a *collection of tendencies* defined on different fitness criteria defined by a given structural configuration. This exemplifies the distinction between goal-directedness in terms of functions, as opposed to germs, the latter defining a tendency operator for a *distribution* of potential paths, in contrast to the former which identifies a state operator defining a single unique path. The "final state" as a "tendency" is associated with the *structure* of the state equation rather than a unique region of the state space. The intention for the final state would define a constraint that selects a tendency. This class of intentional states is associated with adaptive evolutionary systems.

specific final state (or structure) to be the goal. Goal-selection, we shall argue, is the sensitivity of a self-organizing system to nonlocal constraints that have determine local effects, such as breaking ties between competing attractors. By selecting, implicitly or explicitly, among *possible* final conditions, intentional systems go beyond those physical **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 stipulation offered 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 that one which 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 chapter, however, is not to consider the problems 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. From the earlier arguments, 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 General Role of the Perceiving--Acting Cycle: To Conserve Intention

Whenever actions succeed on purpose rather than accidentally, current information must specify what to do 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, that path which best (con)serves the directing intention.

In field-theoretical language, the felicitous perceiving-acting cycle follows a

geodesic,⁷ or streamline, through the ecological field. Thus it defines the optimal goal-path, or 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, nor should we expect, 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. In other words, there is information available in the present which lawfully specifies upcoming future events. Evidence that perception can indeed effect 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 forward flow always attributed to the mechanical-energy-producing action paths (Shaw & Alley, 1985).

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 to 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

⁷A geodesic, or streamline, defines a path which minimizes a metric. Examples are: least work, least time, least distance, least action, least resistance, and so on. The appropriate metric is usually defined as a function of the field's properties.

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 herein. 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, for instance, 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. In this book, whose very title *Behavior: The Control of Perception*, invokes a similar thesis, 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.

Summary

Several concepts relevant to the problems of intentional behavior were introduced in this section, including: germ determinacy as a mechanism for teleological determinism, the relation of the perceiving-acting cycle to intention, and the critical role of perception in providing anticipatory information to support goal-directed behavior. In the following section, these concepts 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 for attempting to unravel the mysteries of goal-directed behavior without depending solely on internal states (mental acts). The cognitivist who wishes more than this, we refer him or her to our lengthy discussions of why we believe this dual-state (organism-environment) approach is sufficient (Shaw, Kugler, & Kinsella-Shaw, 1990; Shaw & Mingolla, 1982; Shaw, & Kinsella-Shaw, 1988; Shaw & Todd, 1980; Turvey, Shaw, Reed, & Mace, 1981).

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

constraints 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-organization. Likewise, the earlier discussion on self-organization provides a background within which to approach this second place.

Constraints on Intentional Behavior

The Perception-action Cycle. A good 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 or her automobile to a controlled stop when approaching the bottom of a hill. The rolling of a car downhill, accelerating due to 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 one's leg so as to achieve a final outcome is quite extraordinary, for it depends on two things that physics and biology ignore: *the choice of an intended goal-state* (e.g., final velocity of the car) as well as *the detection of information* (e.g., the optical flow field) specifying in what manner he or she is to modulate the relevant actuators, that is, through the biomechanical/mechanical linkage of:

leg muscles→*brake pedal*→*hydraulic pressure*→*tire friction/surface friction*.

Without the intending being logically antecedent to the movement, no temporary biomechanical linkage would be functionally (physiologically) assembled nor sustained throughout the act's required duration; and without the detection of the optical flow which 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→*perceiving*→*choosing*→*anticipating*→*assembling*→
(*acting*→*perceiving*→*intending*→*sustaining*→*acting*→ . . . etc.)ⁿ→*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. And 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. As an example, 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 systems 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 code that are materially instantiated within the degrees of freedom associated with the electron states that constitute the computer's memory.

In the profound 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 that which exploits laws relating energy and information in some specific way. In such 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, and so on. 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 actors 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 *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, maintaining 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 nonanalytical (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). These control decisions arise at those points along a trajectory where 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 to integrate the two potentials, and thereby treat 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 crop up 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 involved 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 of high order, it must become escapement dominated (perceptually controlled), so that it might 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. What might qualify as such a motion invariant?

Intention as a "Holonomizing" Constraint

To remain consistent with the already existing inventory of symmetries associated with the conservation laws of physics (see Goldstein, 1980), we must formulate the role that 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. (As the term is used here, a motion invariant is any dynamical variable whose value does not change as the system moves. For classical systems energy, momentum, and angular momentum are 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 which remains conserved, if the action is to be successful. (Mathematically, we might think of this as the characteristic function of the operator.) Elsewhere, we have attempted to give a mathematically explicit formulation of this conserved aspect of intentional systems (Shaw, Kugler, & Kinsella-Shaw, 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 to 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 attractor⁸ of the ecological field (where *ecological field* = the organism as an internal field plus its environment as an external 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, then, is to develop a holonomic description of intentional behavior that bridges the internal field of the organism and the external field of the environment. We will see that the concepts behind self-organization will play an important role in developing such a description.

Internalization of an Evolving Attractor Set: The Embodiment of Geometry

A cognitive approach to intentional dynamics typically puts all the complexity of the problem into internal states of the organism (Fodor & Pylyshyn, 1981; Ullman, 1980). An ecological approach to the cognitive aspects of the problem tends to distribute the complexity over both internal and external states, what might be called a *dual-state* description (Shaw & Todd, 1980). We can use the insights derived earlier from the analysis of self-organizing information systems, as exemplified by the insect nest example, to explain this latter approach to the problem of intentional dynamics.

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 or her daily life, such as, sleeping, eating, working, reading, courting (Iberall & McCulloch, 1969) (see Fig. 23.15). 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 all of the other examples of self-organization described in this chapter, 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.

⁸This attractor may sometimes be defined by a variational principle, but it need not be. For example, mini-max solutions can give rise to an attractor that need not be defined by variational principles.



FIG. 23.15. Examples of behavioral modes that populate an average person's work space.

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 which can not be integrated under the external magnetic field. Hence external (state) field descriptions can not 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 environmental 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 organism. This, we propose, 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 (for details, see Shaw, Kugler, & Kinsella-Shaw, 1990).

It is useful to bear in mind that the field concept is a generic construct; therefore, the set of contents and 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 cognitivist accepts this latter modeling proposition, then consistency demands that he or she must also accept the former. What should be recognized, of course, are the obvious differences that distinguish this ecological approach to cognition and the traditional rule-governed, abstract machine theory (here one might wish to contrast Fodor & Pylyshyn, 1981, 1988, to Turvey, Shaw, Reed, & Mace, 1981, and Carello, Kugler, Turvey, & Shaw, 1984).

Similarly, for both physical and mathematical reasons, it is legitimate to consider the process that takes place in nest building as arising from constraints that are set up by an *internal* field. 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 movement 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 Fig. 23.16, 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 internal to the organism. These attractors are goal-states which 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. Thus, 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 Fig. 23.11, each of the modes illustrated there correspond 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

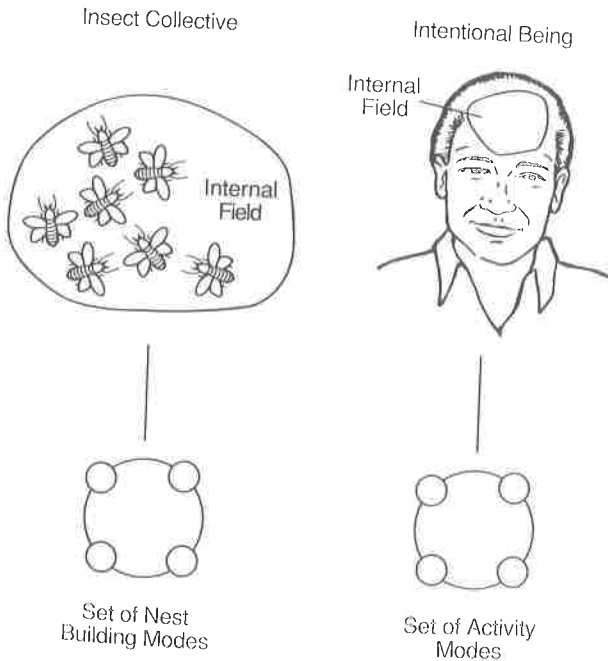


FIG. 23.16. Examples of open systems with cooperative modes defined on internal degrees of freedom.

an internal state description. Previously, we saw 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 on the coupling of two fields—the *external field of the environment* and the *internal field of the organism*. Let us look into this notion of an ecological field more closely.

Intentional Systems as Ecological Fields of Nonstationary Attractor Sets

A single field description, whether it be of the environment (external field) or of the organism (internal field), is only one of many possible descriptions. For example, an organism can be described in many different ways as a function of the mode it is in (as illustrated in Figs. 23.11 and 23.15). 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., size, color, weight, density, and elasticity of the apple). Others, however, 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*, where 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 descriptions also form sets whose members are equally non-privileged. 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 organisms can be described?

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*. As mentioned earlier, 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, Kugler, & Kinsella–Shaw, 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; locomoting 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 Fig. 23.17). 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

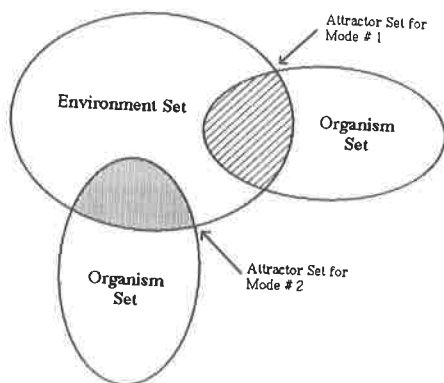


FIG. 23.17. Nonstationary affordance set. The affordance set for an ecosystem is that set of descriptions that is invariant over the state animal and the environment. Since the animal and the environment are both nonstationary, then the common descriptor set (affordances) are also nonstationary.

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 described earlier, all of the generic properties of self-organizing systems are equally important to 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 (the change in the child's ability to sit on various objects evolves over years), 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 or she becomes tired or hurt. Changes in effectivities also play an important role when human operators are required to control complex, technological systems (see Kirlik, 1989, for an interesting example).

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) change. 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. Both the affordance set of relational properties and the set of effectivity mappings among these properties reside in this nonstationary intersection. 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 the internal field (e.g., biochemical processes) and the external field (e.g., gravitational forces). The interesting point, however, is that the coupling between these two fields is dominated by information transactions 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.

The primacy of perception implies that the regularity (i.e., holonomy) 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. For example, if the organism is tired and there is information available which can lawfully guide the organism to a resting state, the organism can still decide to follow another path. The analogue in the insect example, would be an insect which 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.

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

CONCLUSION

This chapter 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 considering the generic mechanisms by which open systems self-organize under energy interactions, on the one hand, and 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 on 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 which realize them.

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 holomically constrained account of intentional behavior that reveals how organisms can become and remain *lawfully informed* in the pursuit of their goals. The generalized theory should provide a means to begin 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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