11

Toward an Ecological Physics and a Physical Psychology

M. T. TURVEY AND ROBERT E. SHAW
Center for the Ecological Study of Perception and Action
University of Connecticut, Storrs, CT, USA

It is reasonably fair to say that the major achievement of the nineteenth century was a formal and rigorous understanding of the previously intuitive idea of "energy" and that the major achievement of the twentieth century has been a similar grasp of the previously intuitive idea of "information," at least as that idea bears on systems of communication. As we peer into the twenty-first century, we can see science shaping up to address the intuitive idea of "knowledge," more precisely of "knowing about" as a property that some material systems can possess with respect to themselves and to other material systems. One suspects that a major scientific goal of the next century, perhaps *the* major goal, will be a formal and rigorous understanding of "knowing about."

In some quarters there may be an argument made that we have already made good progress on this topic, to the point of understanding that the topic is closely related to the exact idea of computation developed in this century as an integral component of science's formal grasp of information. "Knowing about" is a species of computation over discrete symbol strings—that is, representations. From other quarters will come the claim that we are only now beginning to make good progress on this topic given the newly appreciated formalization of a neural network as a parallel communication of continuously graded signals among very many, computationally simple, processing elements. From the neural network perspective, "knowing about" is a species of dynamics—specifically, of the time evolution of neural-like states.

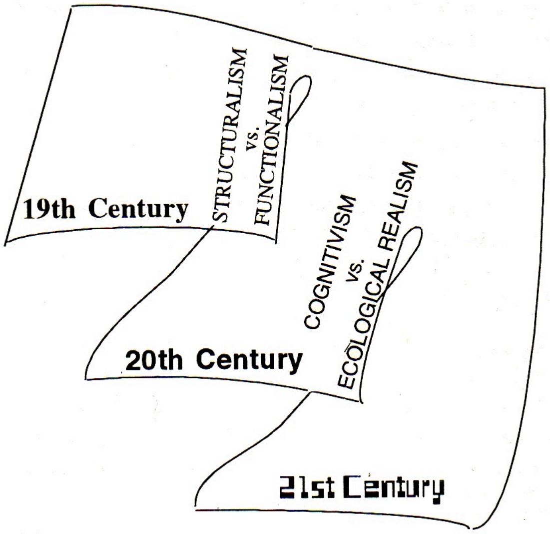
Seen from these two departure points, the challenge of "knowing about" reduces to that of developing and understanding particular mechanisms with the ability to mimic the cognitive phenomena (e.g., memory, language, perception, learning) that characterize organisms, especially humans, and of collecting these achievements into a single unified "knower." For reasons that will become apparent, we suspect that the foregoing attitude-cum-strategy will prove unsatisfactory, and will be (or ought to be) discarded long before the twenty-first century reaches a close. Contrary to the current hopes and aspirations, it seems to us most unlikely that "knowing about" can be equated with, and understood by, the embodying of cognitive capabilities by an arbitrarily chosen material system using processes whose reality is guaranteed only by their implementation (Pollack, 1993). Similarly, it seems to us that the goal of a unified computational account (symbolic or subsymbolic) of cognition is a case of misplaced emphasis.

To be blunt and to the point, "knowing about" as a natural phenomenon will demand a radical extension of physics and, quite possibly, an inverting of the classical understanding that the functional order defining living things (e.g., learning, patterns of mating behavior, directed locomotion in cluttered surroundings) is too special an aspect of nature to sustain universal generalizations of the kind that typify physics (cf. Rosen, 1991). When turned on its head, the classical understanding becomes: *Material systems that express "knowing about" are more general in respect to the principles that underlie them than the material systems that physics currently addresses*. Rather than a reduction of "knowing about" to the contents of any current physics, an amplification of physics by the rigorous study of "knowing about" is envisaged. Again, to be similarly blunt and to the point, it is not the unification of different hypothesized mechanisms of cognitive phenomena that should be sought but rather the *unification of cognition and nature* (see also Pollack, 1993). This sought-after unification is between the laws and principles formative of nature and the defining qualities of material, epistemic systems. Importantly, the assertion above, inverting the ordinary treatment of cognition as special and contemporary physics as general, forewarns that achieving unification will be pursuant to a conceptual revolution in physics that discloses the basis of "knowing about" as generic. It is precisely for such reasons that "knowing about" is so challenging now and will be so challenging for the men and women of the next century: It demands a dramatic, and far from obvious, overhaul of our fundamental orientations, physically and philosophically, toward living things, their surroundings, and the relations that hold between them.

Psychology on the Cusps between the Past, Present, and Next Centuries

Around the beginning of the twentieth century the structuralist and functionalist controversy was in full swing—each claiming to pave the royal road to a scientific psychology. For the structuralists the central question was "What is mind?" and the preferred experimental method was introspection. The method defined psychology as an anthropocentric science. Only humans have language and the ability, thereby, to communicate mental content as immediately experienced. For the structuralists, the view of mind went hand in hand with an acceptance of the burgeoning field of physiology as a way of modeling the brain, the seat of consciousness, and of explaining the connection of the elements of mind to the bodily sensations residing in the brain. Structuralism boasted that psychology was distinguished as a science by its methods for getting to the foundational aspects of mental content and to "mental chemistry" (how elemental experiences combined). Not surprisingly, structuralists championed mind and body as separate and interactive and the belief that volitional thoughts were to psychology what mechanical forces were to physics ("Doesn't the mere thought of moving the body motivate its limbs?").

Functionalism grew out of a positive reaction to the pragmatism of evolutionary biology and a negative reaction to the narrow focus of structuralism's questions and methodology. Rather than being a coherent school comprising single-minded adherents to strict doctrine, as structuralists were, functionalists were eclectic on method and pragmatic about theory. For them the central question was not "What is mind?" but "What is mind good for?". Their quest was not simply to know about mind but to know how mind works in accomplishing adaptive ends for the whole organism whatever its species. Hence, the questions posed by the functionalists tended to be practical, biological, and molar while those posed by the structuralists tended to be disinterested, physiological, and molecular. For the functionalist, the issue was not so much what experiences constitute the mind but what adaptive purposes justify the existence of mind. The functionalist philosophy might best be described as a kind of double aspectism, a neutral monism or perspectival realism, with the mind being viewed as "the brain looked at from the inside" and the brain as "the mind looked at from the outside." Both consciousness and behavior were processes whose streaming through time defied analysis into the fundamental elements sought by structuralists.



The twentieth century has borne witness to many changes in psychology and the branches of natural science to which it is closely allied. Not surprisingly, the opposing perspectives of structuralism and functionalism prominent at the cusp of the nineteenth and twentieth centuries have gone. They were displaced early in the present century by new psychologies such as behaviorism and Gestaltism. As the twentieth century unfolded, however, structuralism and functionalism began to reemerge in new and more compelling forms. A kind of structuralism is the currently dominant perspective in psychological research and theory. Cognitivism interprets mental states as the computational states of a Turing machine or as the time-evolving states of a connectionist (neural network) machine. Cognitivism's lineage is largely structuralism. The inheritance includes a bias toward human intellectual prowess, an emphasis on the physiological underpinnings, and Cartesian dualism (strengthened by the appreciation that mentalism and materialism can coexist comfortably within a computational perspective on mind). The coherence of cognitivism or cognitive science, such as it exists, is induced by a rejection of logical and methodological behaviorism and an embracing of mind as the topic of study. Mind is imbued, however, with functionalistic goals as well as traditional structuralist properties. Where the structuralists at the cusp of the nineteenth and twentieth centuries were strict doctrinaires, the structuralists at the cusp of the twentieth and twenty-first centuries are eclectic, encouraged by the explosion of computer and medical technology to borrow concepts and principles from a multitude of disciplines.

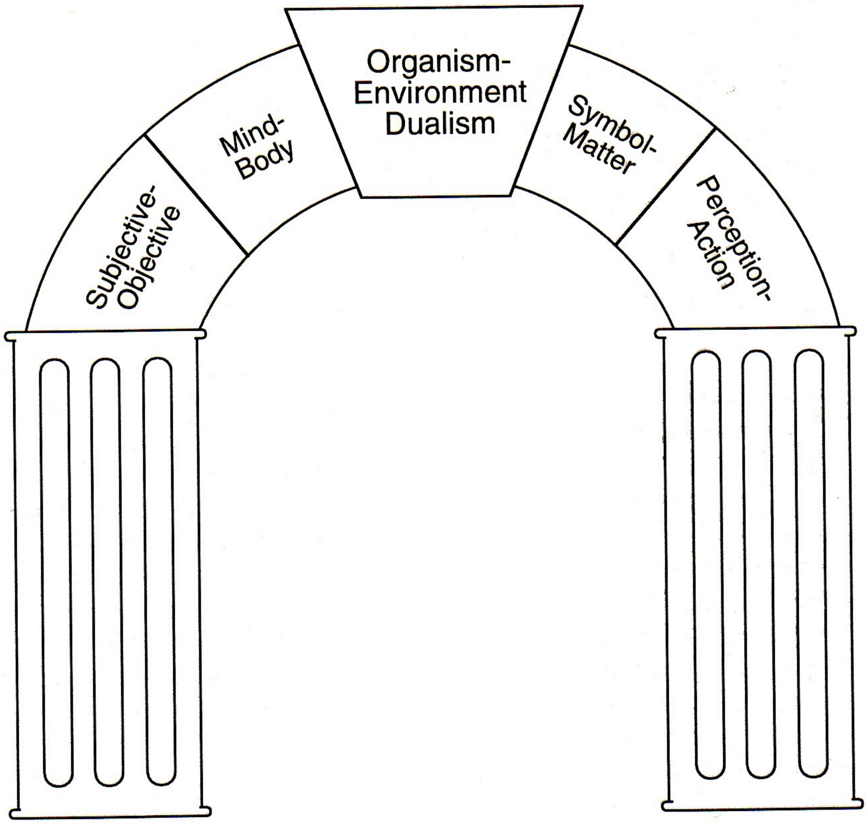
The functionalism to be found at the present cusp between centuries is in the form of "ecological realism," a perspective that emerged in the latter third of the century largely inspired by the American psychologist James J. Gibson. To greater or lesser degree, this perspective is heir to themes developed under pragmatic functionalism (especially as envisioned by the Americans C. S. Peirce, William James, and John Dewey), act psychology (a brand of structuralism), and Gestalt psychology (especially its wholism). Like the functionalism of old, the concerns of ecological psychology are more molar than molecular and its goals focus on the individual adaptability in evolutionarily functional contexts of all organisms, both within and across phyla. The streams of behavior and consciousness that figured prominently in the first round of functionalism are replaced with active organisms qua perceivers engaged in dynamical transactions with their functionally-defined environments. This second round of functionalism, Ecological Psychology, shapes the vision of the future science of mind expressed in the present article.

Organism-environment Mutuality and Reciprocity

The disposition to know is a natural property of a certain class of material systems called organisms. Historically, all attempts to understand this property have been shaped by the metaphysical stance of dualism. Psychologists and philosophers have long referred to the dualism of mind and body, identifying the need for two distinct languages (mentalese and physicalese) to describe what appear to be two radically contrasting aspects of nature. Close relatives of the dualism of mind and body are symbol-matter dualism, subjective-objective dualism, and perception-action dualism. To adopt dualism in any of the preceding forms is to cleave to a particular methodology in which the two things referred to are defined independently of each other, studied independently of each other, and interpreted through independent scientific accounts. Thus, for example, the experimental study of perception and theories of perception have generally proceeded independently of the experimental study of action and theories of action with the upshot that efforts to understand how perception controls action and action enhances perception are forced to introduce arbitrary and special mediators (e.g., schemas, set points, inferential processes). Dualism, therefore, has unwelcome scientific consequences: By sanctifying the logical independence of mind and body, symbol and matter, perception and action, subjective and objective points of view, dualism as a doctrine encourages conceptual divisions in science that give rise to mysteries (vs. potentially tractable scientific problems) that become apparent as soon as questions are raised about how the states or processes in question are connected.

The dualisms mentioned are, in our view, subordinate to organism-environment dualism; it is the keystone that holds them in place, as depicted in Figure 11.1. In a theory of "knowing about," the two principal players are the organism and the environment. Organism–environment dualism establishes the grounds for this theory as the logical independence of the two terms, meaning that a theory of the organism (the "knower") can be built independently of a theory of the environment ("the known"), and vice versa. The presumed logical independence has sponsored theories of "knowing about" in which organisms are continually in the business of figuring out the world in which they act, much like detectives facing the scene of a crime with only vague clues as to the perpetrator. More profoundly,

Figure 11.1. The classical dualisms formative of psychological theory in the present and past centuries are subsidiary to and locked together by organism-environment dualism.



the overarching dualism of organism and environment sanctifies the interpretation of living things as the products of a process—that is to say, evolution, which lies beyond the laws and principles governing inanimate nature, is essentially unpredictable, and contingent (rather than necessary or entailed). Under this conceptual umbrella, the origin of systems exhibiting "knowing about" was a frozen accident, lacking lineage with, and necessary relation to, the generic principles formative of nature. *In our view, the most important conceptual step to be taken in the twenty-first century, with respect to the foundations of a scientific attack on "knowing about," is the rejection of organism-environment dualism and the acceptance of organism-environment mutuality and reciprocity.*

In 1913, Lawrence Henderson published a small volume entitled *The Fitness of the Environment* in which he sought to balance Darwin's evolutionary thesis of the fitness of living things for their environments with an account of the fitness of our planet for life. For example, he addressed the importance of the heat capacity of liquid water in maintaining a relative constant temperature of the earth's surface, a feature essential to the survival of organisms which can function only within a restricted temperature range. Henderson's work was given a mixed reception. Some found it stimulating, others thought it was platitudinous. The investigation of the evolution of the earth as a system, conducted largely since Henderson's time, has affirmed Henderson's hypothesis of the reciprocal fit between living things and their terrestrial surroundings (see Swenson, 1989, and Swenson & Turvey, 1991, for reviews). *A key observation is the increase over geological time of entropy production in the biosphere with the growth and differentiation of organisms.* Figure 11.2A shows a progressive departure of the Earth, as a global single system, away from equilibrium as indexed by the increase in atmospheric oxygen. The transformation of the redox state of the planetary system—from reducing when life first appeared some 3.8 billion years ago, to mildly oxidative some 2 billion years ago, to its presently highly oxidative state—can be taken as a measure of a progressive ordering or internal entropy reduction of the planetary system as a whole. This progressive increase of order in the small, at the scale of the earth, is also a measure—by the balancing requirements of the second law of thermodynamics—of an increasing rate of entropy production in the large, on the scale of the universe.

The atmosphere at the outset of life was mildly reducing, meaning that the earliest life forms were anaerobic, acquiring their energy resources through fermentation. About 3.5 billion years ago, proto-cyanobacteria (ancestors of "blue-green algae") achieved a linkage between the limitless supply of photons from the sun and the essentially limitless supply of electrons in water to bring about the release of oxygen into the atmosphere. As a consequence, life proliferated at an accelerated rate, atmospheric oxygen accumulated (beginning about 2 billion years ago once the oxygen sinks, such as iron formations, were filled) and the planetary redox potential shifted from reducing to oxidative. Atmospheric oxygen functioned as an internal resource or potential that operated over evolutionary time to drive the planetary system even farther from equilibrium.

Figure 11.2B elaborates the preceding theme by showing that not only did terrestrial entropy production increase with an increase in the quantity of order or

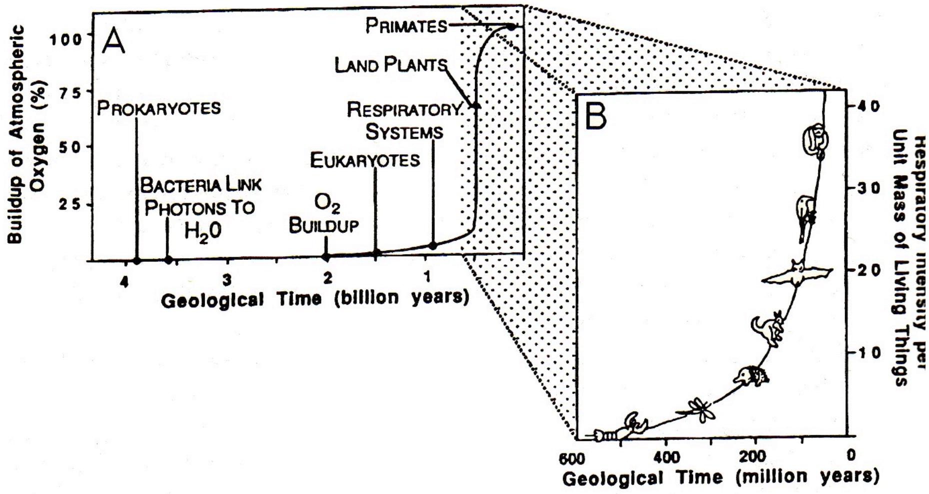


Figure 11.2. Over geological time, measured in billions of years, atmospheric oxygen accumulated gradually at first and then at a (comparatively) rapid pace with increasing numbers and varieties of life forms until it reached its current level of 21% of the atmospheric gases (100% on the vertical axis of Figure A). The accumulation began about 2 billion years ago when the earth's oxygen-binding chemicals became saturated and the oxygen released by bacteria during photosynthesis was free to enter the atmosphere. The oxygen buildup is a measure of a progressive ordering or internal entropy production of the planetary system as a whole. Looking within the last billion years (Figure B), the rate at which the planet's chemical energy was "burned up" through the use of oxygen increased with the rate at which the respiration per unit mass of living things increased as the numbers and levels of living things progressively amplified (pictured in B). An important reading of A and B is that living things and the planet constitute a unitary system abiding by a principle of maximizing the rate of entropy production.

living matter over geological time, but so did the intensity of entropy production. Specifically, Figure 11.2B depicts the respiration intensity per unit mass of living things over the past 600 million years. Aerobic respiration (oxidative phosphorylation) is the process by which living things employ oxygen to release the energy potential from their food. In aerobic respiration, one molecule of oxygen is used for the conversion of each atom of organic carbon. The mass specific respiration intensity is the rate at which chemical resources are dissipated or burned by oxygen into waste or heat products per unit mass of body weight. It is, therefore, a measure of the specific, or per-unit-mass, rate of entropy production. In combination, Figure 11.2A and Figure 11.2B reveal the global nature of evolutionary ordering: Higher-ordered states require higher rates of dissipation to maintain their spatial and temporal extents; the increase in atmospheric oxygen over evolutionary time, due to the activity of living things, provided the potential required for progressively higher-ordered states. As can be seen, the sharp increase in the respiration intensity function in Figure 11.2B corresponds to the sharp increase in the build-up of atmospheric oxygen in Figure 11.2A; the higher-order states acted as sinks that dissipated the oxygen potential.

Schrödinger's (1945) "Life feeds on negentropy" highlights that living things are not equilibrium states but rather steady states maintained away from equilibrium by a continuous flow of energy and matter. A living thing must continually convert energy into organization and thus the order defining a living thing adds ceaselessly to the universal entropy. Figure 11.2A and Figure 11.2B underscore that, with the production of more order, with more numerous and more richly organized living things, and with the progressive production of higher states of order, the additions to the universal entropy are made at a greater rate. To Schrödinger's "Life feeds on negentropy" should be added "Life enhances the rate of entropy production in the large."

In sum, the significance of the phenomena captured in Figures 11.2A and 11.2B is the following: *Living things and their surrounds are not logically independent of each other. Together, they constitute a unitary planetary system abiding by a single and directed evolutionary strategy that opportunistically produces—in progressively more varied and intense ways—the means for the global unit to generate entropy* (Swenson & Turvey, 1991). Organism-environment dualism, a metaphysical hypothesis, is replaced by organism–environment mutuality and reciprocity, a scientific fact that Henderson (1913), most surely, would have acknowledged gleefully. Presumably, this fact of the global relation of Life and Earth is foundational to inquiry into the local relations of organisms and their niches that constitute the subject matter of a science of cognition. It suggests, for example, that there must be reciprocal expressions of organism as knower and environment as known.

Toward a Functional Semantics

Different organisms can occupy the same space or habitat but not the same niche. The term *habitat* refers to where an organism lives, the term *niche* refers to how it lives. The point is that two or more species can live in the same location but to do so they must go about their lives in very different ways. A principle of competitive exclusion is often advanced as the reason for defining a niche abstractly, as that thing in which two sympatric species (those with the same or overlapping areas of geographical distribution) do *not* live. One principal goal of evolutionary ecology is descriptions of the surfaces and substances surrounding an organism that capture uniquely the fit of that organism to its surroundings and clarify the partitioning of any given habitat into distinct niches. In the latter third of the present century, Gibson (1966, 1979/1986; Reed & Jones, 1982) coined the term *affordance* to provide a description of the environment that was directly relevant to the conducting of behavior. An affordance of layout is an invariant combination of properties of substance and surface taken with reference to an organism and specific to an action performable by the organism. An affordance of a change in layout (an event) is an invariant combination of changes in the aforementioned properties, again in reference to an organism and its action potential (Shaw, Flascher, & Mace, 1993). For example, one invariant combination of properties affords grasping by a person, another affords support for climbing by a person, another affords catching by a person, and so on. Affordances are opportunities for action and the perception of them is the basis by which an organism can control its behavior in a forward-looking manner, that is, prospectively. To assume this essential role, however, the term affordance cannot refer to states of affairs that depend on perception or conception for their existence but must refer to real opportunities. From our perspective, this relatively innocuous identification of a niche as a space of real opportunities for action promises to revolutionize the study of cognition.

As an organism moves with respect to its surroundings, there are opportunities for action that persist, opportunities for action that newly arise, and opportunities for action that dissolve, even though the surroundings analyzed as ob-jects and the relations among them remain the same. In the efforts to model cognition in the present century, the knowledge base presumed to be needed by organisms or agents has been identified as denumerable static objects and relations. The affordance interpretation contradicts this presumption. A change of pace or a change of location can mean that a brink in the ground now affords leaping over, whereas at an earlier pace or location it did not. Further, subtle changes of action can give rise to multiple and marked variations in the opportunities for subsequent actions. The environment-for-the-organism is dynamic and action oriented while the environment-in-itself, that which has been the target of most modeling in the latter decades of the present century, is fixed and neutral with respect to the organism and its actions (Kirsch, 1991). *The new century will witness a thoroughgoing attempt to build a functional semantics if for no other reason than the need to build robots that work with respect to environments that are real (Effken & Shaw, 1992).*

Can we catch a glimpse of the building blocks of this function-oriented semantics? In conventional physical analyses, the property of a thing that is potential, or latent, or possible—that is, not occurrent—is referred to as a *disposition*. The primary characteristics of a dispositional property are three in number and they are basic to developing the notion of affordance. First, the disposition to do something is prior to doing that something. For example, a crystal will actually refract light provided that it is refractive to begin with; if it was refractive to begin with, then it was so whether or not it was exposed to light. Second, dispositionals (or causal propensities) come in pairs. For example, (all) light rays are refracted if and only if (some) pieces of matter are refractive. In respect to the organism-environment mutuality and reciprocity thesis, it is noteworthy that reciprocity occurs in the very definition of a dispositional property. Third, dispositionals never fail to be actualized when conjoined with suitable circumstances. The character of an affordance can now be more clearly expressed—it is a real possibility, it is a dispositional property, and it is reciprocated or complemented by another dispositional property: an effectivity. An *effectivity* is the causal propensity for an organism to effect or bring about a particular action. Whereas an affordance is a disposition of the surrounding environment, an effectivity is the complementing disposition of the surrounded organism (Shaw, Turvey, & Mace, 1982; Turvey & Shaw, 1979). Thus, an affordance is a particular kind of physical disposition, one whose complement is a property of an organism (Turvey, 1992). The upshot is that, from the perspective of investigating "knowing about," an organism and its niche constitute two structures that relate in a special way such that understanding of one is, simultaneously, an understanding of the other. If the form of this special relation could be made precise, then an important step would be taken toward understanding the class of material systems that exhibit "knowing about."

Mutuality implies a sameness—a commensurate dimension—over which organisms and their environments might transact business. But the relationship between organism and environment must reflect their different functions in the ecosystem—a bipolar dimension over which they act and react in reciprocal but distinct ways that nevertheless fulfill one another. Consider the analogy to numbers that add up to one: They are mutual in that they may be added to one another (symmetry) but reciprocal in that they may have different values (asymmetry). The symmetry property can be reconciled with the asymmetry property by moving to a higher-level of analysis, namely, to the notion of the numbers being complementary in the sense that they complete one other. Likewise, taken together, the organism and environment may be mutual and reciprocal—symmetric and asymmetric—but at a higher level they are complementary duals; they combine to make a whole—an ecosystem. It is apparent, therefore, that the asymmetry of dualism (where organisms and environments are merely incommensurate kinds) must give way to the symmetry notion of *duality* (where the two are commensurate kinds), otherwise there can be no synergy, without which there could be no ecosystems. Under this synergy, biology and physics come together with psychology to define a science at a new scale, the ecological scale, at which physical law might conceivably become more unitary. The alternative treats the relationship between knower and known as a metaphysical dualism, with the organism as knower and the environment as the known, coming under different laws, or worse, viewing the environment as being lawfully independent of its function for supporting the organism, and the organism, as a perceiver-actor, whose functions lie outside the scope of any law.

In sum, the special relation in question between organism and environment seems to be the particular kind of isomorphism captured by the mathematical notion of duality. Duality is an abstract rather than a concrete idea; it refers to a relational property, a correspondence, holding between a pair of mathematical objects. The duality holds, even if two objects are of unlike kind, so long as some property of the first object plays the same role among its total property set as that played by a property of the second object among that object's total property set. For example, with respect to a series of perceptions and a series of actions, as might be exhibited over time in fulfilling a goal, a duality would be an operation that establishes a correspondence between the properties of the two series even though the two are quite different (Shaw & Alley, 1985).

The discussion of duality that was initiated by the implications of Figure 11.2 and encouraged by the issue of a functional semantics has, in the immediately preceding comment, focused upon the fit between perception and action under an intention to do so and so. Most of what follows is concerned about the steps needed to understand that fit.

Controlled Locomotion as the Paradigmatic Form of "Knowing About"

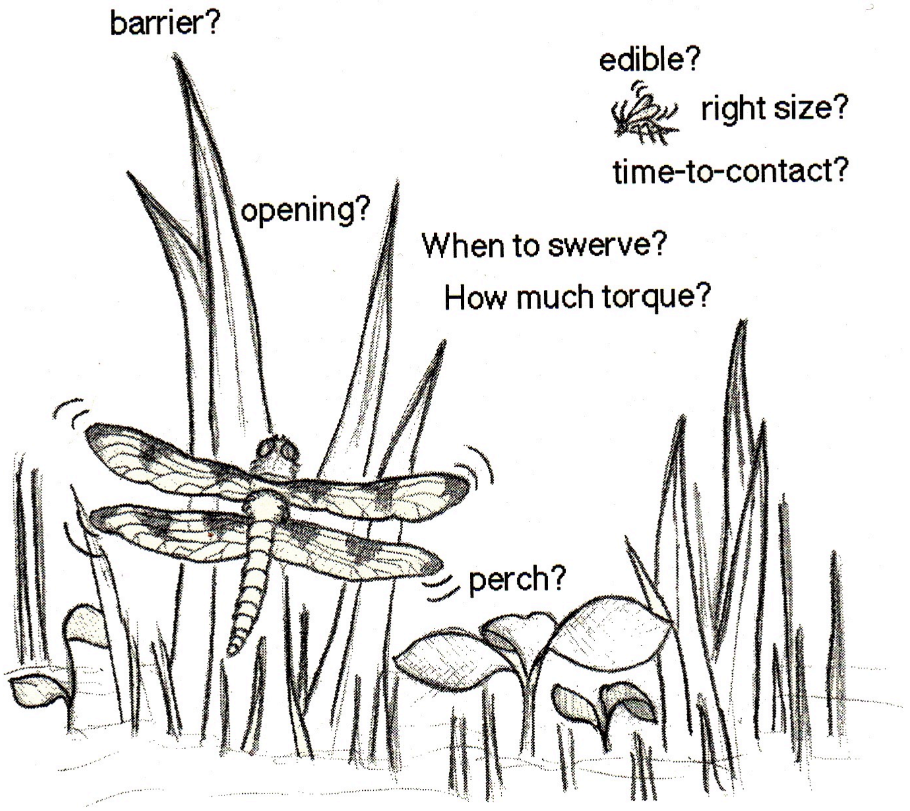
For most scholars grappling with cognition in this final decade of the twentieth century, the dominant tendency is to equate knowledge with concepts and to inquire about their form and about the inferential processes (explicit when cognition is defined as symbol manipulation and implicit when it is defined as connected subsymbols) that operate upon them. The grounding of the concepts—that is, how they can refer to the environment of the knower—and the origins of the constraints on the inference mechanisms—that is, the reasons that these mechanisms should function in just that way that renders their consequences sensible (meaning that one could, in principle, act upon them)—are not of paramount concern (for criticisms of this attitude from our perspective, see Carello, Turvey, Kugler, & Shaw, 1984; Turvey & Shaw, 1979; Turvey, Shaw, Reed, & Mace, 1981; for similar criticisms from within conventional cognitive science, see Harnad, 1990; Johnson-Laird, Herrman & Chaffin, 1984). In sum, cognition tends to be investigated as a disembodied, rational process: Concepts and inference mechanisms can be lifted away from the organism-environment systems, and perception-action subsystems, that express them, and modeled in their own terms. Accentuating the already troublesome features of this modeling strategy is the fact that it requires a designer who must determine what constitutes the objects, events, and relations to be conceptually represented on the basis of his or her own experience, creating a frozen (static) ontology peculiar to the designer's whims (Carello et al., 1984; Clancy, 1992; Turvey et al., 1981). A major promise of the neural network perspective is that the preceding difficulty is circumvented because concepts in that perspective are not prescribed but emergent, arising from the interactions among very many subsymbolic processing units. Unfortunately, a critical examination of NETtalk (Sejnowski & Rosenberg, 1987), often offered as the primary example of successful emergence, reveals that the conceptual distinctions eventually exhibited by the network are already implicitly coded by the designers into the patterns fed to the network (Verschure, 1992).

The disembodying of cognition is consonant with organism–environment dualism and reinforced by the choice of what counts as a paradigmatic cognitive phenomenon. Popular choices are the human capabilities of syntax, problem solving, remembering, expert knowledge, and the like. These phenomena seem to be so focused *at* or *in* the individual, and so trivially dependent on the current environment and ongoing behavior, that they invite analysis in purely formal, abstract terms and the modeling of the environment and behavior (conceived as inputs and outputs, respectively) in the same abstract terms. In consequence, broaching the problems of how the symbols, inference mechanisms, and task ontologies are grounded rarely occurs in the context of the preceding choices of paradigmatic cognition. And even if an attempt were made, it is not clear that these research domains can provide a sound basis for addressing the grounding issues. We have two reasons for this pessimism: First, grammar, problem solving, remembering, expert knowledge, and the like, are too far beyond the pale of the current stock of scientific tools by which nature's phenomena are understood in general law-based terms, reducing thereby their potential as a basis for substantial progress;

second, and perhaps more important, they cannot be considered as fundamental forms of "knowing about" nor can they be considered as having posed major challenges in the evolution of material systems with the property of "knowing about." Returning to Figure 11.2, most of the past 3.5 billion years seem to have been consumed by the establishment of the ability to move in a controlled and directed manner—to tumble, crawl, walk, run, jump, fly, swim, slide, burrow, and so on, among the environment's persistent and variable clutter, perceiving the actions the material layout allows with sufficient efficacy to discover energy resources and to implement the circumstances for procreation. We suspect that grammar, problem solving, remembering, expert knowledge, and the like, are capabilities that arose straightforwardly once controlled locomotion, at each and every length scale occupied by living things, was firmly in place (see also Brooks, 1991). On these considerations, scientific inquiry into "knowing about" begins with *controlled locomotion*. What will become extremely apparent as we examine what is involved in controlling locomotion is that *understanding "knowing about" will demand both a broadening and an enrichment of the current understanding of "energy" and "information," an appreciation of the confluence among all three intuitive ideas, and a physically grounded understanding of an even more inexact idea, namely, "intention."*

Figure 11.3 depicts a dragonfly weaving its way about in a thicket of the kind

Figure 11.3. Controlled locomotion by a dragonfly is a very cognitive matter.



typifying New England in the summertime. A dragonfly feeds on small insects, such as mosquitoes. In seeking its prey, the dragonfly must perceive paths through the thicket. To do so, it must perceive obstacles to its forward locomotion and openings that permit it passage, given its size. Given the many objects within the thicket—insects, birds, leaves, berries, flowers, and so on—the dragonfly must perceive selectively those objects that are edible for it, commonly insects within a certain length scale and degree of softness. It must also perceive places that it can alight upon, places to rest between searches. In traveling through the thicket and in direct pursuit of a prey, the dragonfly must perceive when an upcoming twig or an upcoming prey will be contacted if current conditions (wing torques, forward velocity) continue, so that suitable adjustments can be made both with respect to the body as a unit and with respect to the most forward limbs that are used to effect a catch or a landing; it must perceive the amount of required rotation, elevation, and yaw in 3-dimensional space when it and a prey are not aligned; it must perceive the distances of prey, when more than one is within range; and it must perceive when to decelerate, and whether it is decelerating appropriately when the catch is close to occurring and similarly when it is descending onto a perch.

The dragonfly-thicket system expresses why it is that controlled locomotion is such a fundamental form of "knowing about." To satisfy its intent in the thicket, the dragonfly must know where it is, where it can go, when it can go, and how it can get there. Let us see what kinds of things students of cognition in the twenty-first century may have to grapple with in order to account for how the lowly dragonfly locomotes successfully.

Direct Perception

The dominant view of perception on the cusp between the twentieth and twenty-first centuries is that it is very much a matter of inference, very much a process that involves reasoning-like steps, albeit "unconscious and irresistible." To a significant degree, this view is shaped by the widely held understanding that the light distributions available to the eye, the sound distributions available to the ear, and so on, fail to specify the properties of organism-environment systems. The energy patterns ambient to an organism are traditionally thought of, at best, as containing cues or clues to the world. Consequently, in the standard view of the twentieth century, "perception" becomes a roundabout or indirect way of getting acquainted with, and maintaining contact with, one's surroundings. Perception is interpreted scientifically as a kind of justification, via inference, of an organism's perceptual beliefs. This interpretation, which casts perception in the mold of proposition-making activity with either true or false consequences, renders perception a potentially questionable basis for an organism knowing about its surroundings.

The ecological approach places tight constraints on the use of the term "perception." By promoting a conception of law that allows meaningful relations between organism and environment to hold, it constrains the use of the term "perception" to relations governed by such laws. Further, it reserves the term "perception" for designating only really possible and actual states of the organism-environment system. These constraints on its usage vindicate perception as *the* incorrigible basis for an organism knowing about its surroundings (Turvey et al., 1981).

Consider the statement *"O* perceives *E,"* where *O* stands for organism and *E* stands for an environmental property. Under the ecological analysis, this statement presupposes a law, *L*: A property *P* of an ambient energy distribution (e.g., light) is lawfully related to *E* in that it is unique and specific to *E* in *O*'s niche. Now, given *L*, *"O* perceives *E"* designates a factual state of affairs if (1) *E* is present, (2) the *P* resulting from (1) and *L* is available to *O*, and (3) *O* detects the *P* defined in (2). *The incorrigible basis for an organism "knowing about its environment lies in the satisfaction of* L *and the three conditions.* The statement '*O* perceives *E*' picks out a property of the organism-environment system emergent when *L* and the three conditions are fulfilled. The importance of calling it a "property" is that a property (as opposed to an attribute or a concept) is present or absent, existent or nonexistent, but not true or false.

Given the satisfaction of *L* and the three conditions, an organism (in principle) is directly aware of *E*. In the formulation dominating the twentieth century, an organism is directly aware of something else—such as the states of its nervous system or of an internal representation—and only indirectly aware of states of the world. The notion of perception as indirect goes with organism-environment dualism; the notion of perception as direct goes with organism-environment mutuality and reciprocity.

Physicalizing and Intentionalizing Information

Consider the possibility already identified that the emergence and extension of material systems exhibiting "knowing about" accords with a physical selection principle, namely, those things, processes, etc., are selected that increase entropy production at the fastest rate. This consideration provides a glimpse of how it could be possible that cognition is intimately connected to principles of the most generic kind and not merely a contingent feature of nature at the terrestrial scale: Material systems with the property of "knowing about" can interact in more diverse ways with their surroundings than material systems restricted to force-based interactions, extending, thereby, the opportunities for the global system to degrade energy.

Colloquially, one would say that the interactions between organism and surround typifying "knowing about" are information-based. Consider, for example, the dragonfly vis-á-vis thicket in Figure 11.3. In speaking this way, however, one seems to be using the term information in a very different sense from the mathematical formulation of information as the minimum equivalent number of binary steps by which a given representation may be selected from an ensemble of possible representations. This mathematical theory of information was developed to address the formally defined states of affairs of communication and representation and not the physical states of affairs by which informed interactions might occur between an organism and its surround. It is a theory suited, at best, to the organismic capability of discriminating. Within the theory, information processes are viewed as selection processes that must be made from among a specific set of alternatives; and if the selections are to convey information, the set of choices must be known in advance. But discrimination among members of a set presupposes that the members are perceptible, meaning that the capacity to discriminate is derivative and, by itself, a poor basis for "knowing about." Furthermore, foreknowledge of the environmental entities to be encountered is incompatible with the intuitive understanding that information detection should be the basis for adjusting behavior to novel circumstances. Organism-environment interactions require information in the sense of information *about* something, information specific *to* something; that is, information of a kind that permits the perception *of* something rather than the discriminating among things (Gibson, 1966, 1979/1986). Even more poignantly, the actions by which "knowing about" is expressed require that information about environmental facts be referential to the energy for behaving with respect to those facts. For the dragonfly of Figure 11.3 aiming itself at a prey, to see the distance-to-contact is to see the work required, to see the time-to-contact is to see the (schedule of) impulse forces required, to see the direction-to-contact is to see the torques required (Shaw & Kinsella-Shaw, 1988).

In sum, the response in the twenty-first century to the challenge of "knowing about," a challenge expressed quite substantially by our dragonfly, will require a theory of information that takes information to be physical—that is, a law-based property of real states of affairs as opposed to simply a logical or mathematical attribution. Pursuit of the theory will consist, in significant part, in the empirical determination of properties of ambient energy distributions that are specific to behaviorally relevant properties of organism-environment systems. A lot of mathematics and physics will be needed in this enterprise, and much of it will have to be developed. Importantly, in keeping with the argument that systems expressing "knowing about" are more general in respect to the principles that underlie them than the systems accommodated by contemporary physics, it will have to assume that the intuitive idea of information *in its most fundamental form* can be captured only in organism-environment systems. The development of the requisite understanding will be founded on answers to questions such as: What kinds of energy magnitudes and energy forms are involved? What kinds of structures carry or contain information? What are the physical conditions for generating information? What is the (thermodynamic) cost of detecting it? How is information connected to dynamics? How is information perspectival, that is, scaled to the systems that use it? Let us see what directions the answers to some of these questions are likely to take.

1. *What kinds of energy magnitudes and energy forms are involved?*

Oddly enough, this question is closely linked to the question of what makes a system complex. There are a number of ways of addressing this complexity question in present-day science, but the most basic, and at the same time the most relevant for our present purposes, focuses on the degree to which the flows of energy from the interior to the exterior of a system can be time-delayed (Iberall & Soodak, 1987; Yates, 1986). The ability to delay external-to-internal-to-external-to… energy flows affects dramatically a system's mode of interaction with its surroundings; the system's enslavement to the external force field is weakened. The time-delaying of energy flows provides a local, internally based, source of forces that can compete actively with the external forces. Our dragonfly can fly against gravity and into a breeze. As system complexity magnifies—that is, as the internal forces increase with respect to the external forces—system-surround interactions will become increasingly less dominated by force (dimensionally, MLT^{-2}), momentum (MLT^{-1}), and kinetic energy (ML^2T^{-2}). That is, the basis for the interactions will become increasingly less dependent on observables defined through the mass (M) dimension (Kugler & Turvey, 1987, 1988) and increasingly more dependent on observables defined solely through the dimensions of length (L) and time (T). These observables are geometric (fashioned from L), spectral (fashioned from T), and kinematic (fashioned from both, for example, LT^{-1}, LT^{-2}).

Consider that living things are immersed in energy distributions; our dragonfly, for example, is immersed in light. The forces impressed upon them by these enveloping distributions are low relative to the forces that can well up from the interior of organisms—for example, the forces of enveloping optical distributions or enveloping distributions of volatile materials with respect to the forces generated by a flying insect or a running mammal. It is these low energy distributions that connect the dragonfly to the thicket's behavioral opportunities or affordances. They are the basis for force-free epistemic contact to be contrasted with the forceful nonepistemic contact characteristic of the systems-and-surrounds studied in classical mechanics.

2. *What kinds of structures carry or contain information?*

The descriptions in the optical case, for example, are of the spatio-temporal structure—that is, the adjacent and successive order—that is imposed on the ambient optical distributions by the layout of environmental surfaces (attached and detached objects, places, one's body, movements of one's body, surface displacements, deformations, collisions, etc.). An ecological conception of information is founded on the assertion that invariant relations exist between layout properties of general significance to the governing of activity (affordances) and macroscopic, noninertial properties of structured ambient (optical, mechanical, chemical) energy distributions (Gibson, 1966; 1979/1986). The latter, therefore, can specify the former. In the case of the dragonfly of Figure 11.3, the structured light available during flight consists of transformations of different intensities, spectral contrasts, and specular highlights in different directions. The mathematics and physics of fields are needed to reveal, for example, the optical properties lawfully generated by gaps that are pass-throughable and by edible objects that are interceptible.

The distinction between information about something and the something in question deserves emphasis. Fields of diffusing volatile materials fill the air and are ambient to each and every animal. The sources of these odors are other animals and their products, plants and their products, and a few types of inorganic things. (For the most part, the minerals of the earth, the air, and the water, are odorless.) The information carried by a diffusion field specifies its source but is not chemically identical with its source. Thus, the body odor of an individual animal is specific to its body but does not have the same chemical composition. Behind the explication of the information carried by fields of diffusing volatile materials is an ecological chemistry. This chemistry expresses the fact that some vapors (and, in the case of tasting, some solutions) are informative about their sources without being chemically identical with them. Analogous tasks confront ecological optics (Gibson, 1961; Reed & Jones, 1982), ecological acoustics (Gibson, 1966; Lee, 1990; B. Shaw, McGowan, & Turvey, 1991), ecological mechanics (Gibson, 1966; Solomon, Turvey, & Burton, 1989), and so on.

Also deserving of emphasis is the distinction between available information and detected information. Energy distributions ambient to a point of observation are structured in ways specific to the surface layout surrounding the point of observation and to the point of observation's position relative to those surroundings. They provide, therefore, opportunities for "being informed," more essentially, for planning and controlling goal-directed behavior. These opportunities exist because of the the invariant relations between the properties of the surround and observation point and the properties of structured ambient energy distributions. These opportunities are not dependent on living things; they are simply available as a consequence of the lawful regularities at the ecological scale. It is, however, to be understood that the laws of information, like the laws of mechanics, electromagnetism, and thermodynamics, are necessarily involved in the makeup of living things. The meters (perceptual systems) and actuators (muscle synergies) of organisms can no more lie outside these information laws than the metabolic, respiratory, circulatory, hormonal, etc, processes can lie outside the mechanical, electromagnetic, and thermodynamic laws.

3. *How Is the Information-That-Is-Detected Related to the Energy-That-Is-Controlled?*

Given an onboard source of energy (e.g., chemical energy carried in the muscles), what are the constraints on its deployment to bring about directed movements? Perception by the dragonfly of the direction-to-contact with a mosquito is rendered as the application of a specific torque to bring about the coincidence of axes— of dragonfly and prey—in 3-dimensional space. Patently, to generate this specific torque, the dragonfly must allocate a specific amount of its energy resources. At first blush, information about direction-to-contact and the energy for torque-to-contact seem to be two very different and unrelated things. If they are indeed so very different then it is difficult to comprehend how the dragonfly, or any other creatures such as ourselves, can routinely interconvert them. The daily challenge of directed actions would be analogous to attempting to convert one currency into another (e.g., deutsche marks for dollars), routinely and reliably, in the absence of an exchange rate. If information and energy are independent and without a common basis, then the conversion must be arbitrary and the fitting of actions to the surroundings a matter of happenstance. In our view, the strong version of organism-environment mutuality implies that information and energy are logically dependent and relate in the double dual manner expressed above (Shaw & Kinsella-Shaw, 1988). This a profoundly important hypothesis about the two focal topics of the past and present centuries: *When properly understood, information and energy are reciprocal aspects of nature. This reciprocity is neither required nor revealed by a physics that considers natural systems that exhibit the quality of "knowing about" as special systems. The reciprocity is brought to the forefront only when systems exhibiting "knowing about" are understood as more general in respect to the principles that underlie them than the material systems currently addressed by physics.*

That there may be a common and intrinsically defined energy-dissipation principle underpinning animal activity is suggested by the following remarkable fact: Locomoting animals exhibit an independence of energy cost and speed such that the amount of energy used to run a given distance (say, 10 m) is nearly the same whether it is run at top speed or at a leisurely pace. When mass-specific rates of energy consumption are plotted, as in Figure 11.4A, for a given animal as a function of locomotory speed, a straight line is obtained from an intersect with the vertical axis at zero (e.g., Full, 1989). This linear dependency of mass-specific rate of energy consumption on speed holds for bipeds, quadrupeds, and polypeds, for arthropods and vertebrates, for limbed and limbless animals. It is a dependency of great generality, suggesting a fundamental principle governing locomotion that is independent of morphology, physiology, size, and taxa. Spelling out the types of quantities involved in the linear dependency we see that

$$\text{Net cost of locomotion} = \frac{\text{Energy per unit mass/Time}}{\text{Distance/Time}} = \frac{\text{Energy per unit mass}}{\text{Distance}}$$

That is, the net cost of locomotion indicates the amount of energy required to move a unit mass of animal a given distance. The slope of mass-specific rate of energy consumption vs. speed varies inversely with mass, as shown in Figure 11.4B. On the basis of the empirically determined slopes, it can be concluded that to move a unit of mass 1 meter, a cockroach of 3 grams dissipates twice as much energy as a crab or mouse of 30 g and nine times as much energy as a dog of 3 kilograms; small animals on a per gram basis require more energy per time and per distance. Conversely, if an arthropod, a reptile, a bird, and a mammal, have similar mass, then the energy to be dissipated by each to move 1 meter will be nearly identical.

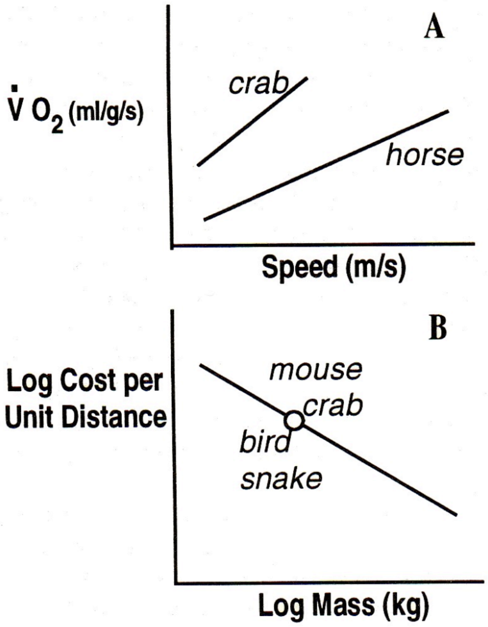


Figure 11.4. (A) As a crab and a horse run faster, the energy they expend increases in direct proportion to their speed, more so for the lighter crab, however, than the heavier horse. For both crab and horse, the constant slopes mean that the cost of traveling a given distance is a fixed amount, regardless of speed. (B) This constant cost depends on the mass of an animal. Animals different in form and locomotory style but of the same mass require the same amount of energy to move the same given distance.

We might hypothesize, therefore, that the dragonfly of Figure 11.3 is relieved of the burdensome task of determining how much energy to use for this or that path through the thicket at this or that speed by a fundamental principle that is at once thermodynamical and informational. The form of this principle escapes current science, but its relevance to everyday locomotion has been duly, if implicitly, appreciated by dragonflies for well nigh 350 million years.

Intentional Behavior as a Symmetry of the Ecological Scale

The dragonfly's perceiving and acting are conjoint in that they serve a mutual aim (catching small insects and maintaining, in consequence, onboard energy resources). At the same time, they are disjoint in that they serve that aim in reciprocal ways, by the detection of information that constrains action and by the performance of actions that constrain perception. In a circularly causal manner, the dragonfly's perceiving alters its actions engendering, thereby, new opportunities for perceiving and entailing, thereby, further modifications of its actions. Intuitively, understanding the conjointness and disjointness of perception and action is a cornerstone of the theory of "knowing about."

The dragonfly's pursuit of prey is an example of intentional behavior. Such purposive movements (Tolman, 1932) or goal-directed actions are a hallmark of living things and are as commonplace terrestrially as the motions addressed by physical theory. Cybernetical efforts to capture intentional behavior, conducted for most of the latter half of the present century, sought to render intentional behavior as a combination of initial conditions (a set point) and control laws. Rather than providing understanding, this move regressed the general problem of intentional behavior to the highly particular problems of how and for what purpose given systems were designed (Kugler, Shaw, Vincente, & Kinsella-Shaw, 1990; Weir, 1985).

The thesis that systems expressing "knowing about" are the most general in respect to the principles that underlie them, suggests that intentional behavior is likely to demand a physical account of the most profound kind, with extremely broad implications. In contrast to the material systems that have come under the scrutiny of past and present physics—systems that must be aimed by extrinsically imposed initial conditions (classical mechanics) or pulled by a preexistent attractor (deterministic chaos)—a material system such as the dragonfly literally aims itself toward targets. Stated more completely, the dragonfly as an intentional material system exhibits both a significant insensitivity to extrinsically imposed initial conditions (the thicket is cluttered in variable ways at all length scales, a fact which the dragonfly does not seem to find overly bothersome) and an uncommon sensitive dependence on final conditions (a mosquito is usually caught, regardless of the number and variety of impediments) (Shaw & Kinsella-Shaw, 1988). It is as if the transformations of perception and action leave invariant the dragonfly's state of "wanting that it catch that particular mosquito" (philosophers sometimes refer to verbs that are followed naturally by "that" as *intentional idioms*). Relatedly, it is as if the dragonfly's intending, or "wanting that it catch that particular mosquito," binds the variables of information detection, energy control, and goal state, in a special way so as to effect a geodesic (a least distance, least time trajectory) and to conserve some particular (but as yet unknown) quantity. These observations suggest that a useful approach to the natural phenomenon of intentional behavior can be provided by the mathematical theory of groups, a tool to which physics has turned repeatedly this century with great success whenever and wherever issues of invariance and conservation arise. A *group* is a set *G* of transformations or symmetry operations equipped with three rules: Any two operations can be combined to give a third (and this product is associative), there is one that does nothing at all (the identity), and every operation has an inverse (the combination of the two being the identity). A *group* is closed. No elements outside *G* are attainable by combining elements contained within *G*. In its applications in physics, a group is a measurement device that reveals certain, ideally essential properties, while ignoring others. Can a group be defined that captures the minimal essential structure, the basic symmetry, of intentional behavior? And if so, what hidden structure is it likely to disclose?

Our suspicion is that overseeing any efforts to identify the symmetry group for intentional behavior should be the thesis of organism–environment mutuality and reciprocity, strongly interpreted (Shaw, Kugler, & Kinsella-Shaw, 1990). This thesis dictates a number of reciprocities. Some aspects of intentional behavior refer to an interior frame of reference, the biology of the dragonfly. Other aspects refer to an exterior frame of reference, the thicket surrounding the dragonfly. By the strong mutuality thesis, the processes referred to these two frames should be reciprocal. Similarly, some aspects of intentional behavior are *hereditary*, in that what is happening now is entailed by what occurred previously, and other aspects are *anticipatory*, in that what is happening now is entailed by what will happen next. By the strong mutuality thesis, these past-referring and future-referring processes should be reciprocal. Also by the strong mutuality thesis, a reciprocity should exist between the informational and energetic aspects of intentional behavior, a reciprocity that has already been underscored in remarks above.

It is roughly apparent that fulfilled intentional behavior, such as the dragonfly maneuvering through the thicket to nab a gnat, consists of four operations: detecting information, intending a particular goal, controlling energy, and successively realizing the goal. In order to lay hold of the symmetry of intentional behavior, we will need to represent these operations in a manageable form. We need to assign numbers to them. Two of these operations act on states in the exterior frame of reference—detecting information about the environment and one's self, and controlling energy to bring about specific movements of one's self with respect to the environment. The other two operations— intending a goal and realizing it—act on states in the interior frame. Capturing the contrast between the exterior and interior pairs can be achieved by using the real numbers $+1$ and -1 to represent the exterior pair as real operators and by using the imaginary numbers $+i$ and $-i$ to represent the interior pairs as imaginary operators. Since information about an environmental fact is a basis for anticipatory control, its detecting can be treated as the operator -1, to convey its acausal, time-backward nature; in contrast, the energy controlled to move in a particular manner, as the basis of hereditary control, can be treated as the operator $+1$, to convey its causal, time-forward nature. In a similar vein, since intending a goal is anticipatory and realizing a goal is hereditary, these can be treated as the operators $-i$ and $+i$, respectively.

Figure 11.5 depicts the preceding mathematical structure for the dragonfly of Figure 11.3. It defines a group (operations are associative, each has an inverse, and there is an identity). The question posed was how the variables of information detection, energy control, and goal state are bound together under the mosquito-catching intent. That they might do so by virtue of a group structure provides an answer that points to symmetries at nature's ecological scale shaping the functional order characteristic of that scale. We underscore the significance of symmetry in our final remarks.

Direct Perception: Symmetry Again

It is fairly obvious that perception is *the* means by which organisms know about their surroundings. The dragonfly picks its way through the thicket and aims itself at suitable prey by means of perception. If perception is not merely contingent

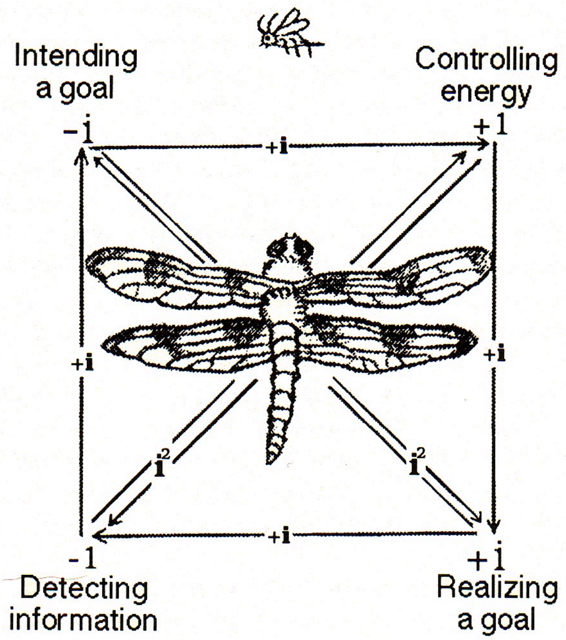


Figure 5. The persistence of an intention (“catch that mosquito”) over variations in information detection, energy dissipation, and proximity to the “catch,” together with the coherent fitting together of these variations, invites a group structure analysis. The depicted group is a cyclic group with its four operations linked by the flow operator *i*.

but entailed, following necessarily from maximizing the global rate of entropy production, then perception is a phenomenon to be understood in terms of lawful regularities and symmetry principles defined at the ecological scale of organisms and environments, rather than in terms of mental states, and formal languages of representation and computation. This leads to what may well prove to be, in the next century, the most important handle for taking hold of “knowing about” in a rigorously scientific manner—namely, *the understanding that perception must be “direct”* (that is, achieved direct apprehension without intermediaries such as inference or matching to mental schemas). This handle, fashioned for us in its contemporary form by Gibson (1966, 1979/1986), provides a means for appreciating organisms as knowers and the environment as known in mutually compatible terms. Direct perception is consonant with organism-environment mutuality and reciprocity: Where the interpretations of perception that have dominated the past and present centuries have portrayed the dragonfly and its surroundings in disharmony, perception as direct renders the dragonfly and the functional description of its surroundings harmonious. Very importantly, direct perception does not create the epistemological paradoxes that have befallen all other theories of perception, paradoxes that would be expressed by phrases such as “the dragonfly’s visual system invents its surroundings,” “the thicket and prey are illusions of the dragonfly’s brain,” “the dragonfly has foreknowledge of space,” “the dragonfly has foreknowledge of the basic concepts needed to interpret the signals from its sensory organs," and so on. For Gibson, perception is specific to the environment and to self-movements because (1) information is specific to the environment and to self-movements, and (2) perception is specific to information.

Specificity is an intuitive idea of considerable power, as highlighted in our expectations for a biologically-relevant information theory. It should become evident in the next century that the top priority of a science of cognition is a *general theory of specificity*, of how one thing can specify another and how specificity can be preserved over different and time-varying components of an organism-environment system (e.g., the components of the dragonfly-thicket system and the perception-action cycles that it manifests). This contrasts with the pursuit by many scholars in the latter part of the present century for a general theory of representation (e.g., Fodor, 1975). What is gained from the specificity of perception to the environment and self-motion? Nothing less than the grounding of "knowing about." Patently, for those who would seek a general theory of representation, any viable theory of what concepts an organism may be said to have and how they might be said to refer, presupposes and requires a theory of specification (Shaw et al., 1982).

The directness of perception follows, presumably, from nature being constrained in particular ways. Consequently, science in the twenty-first century can expect to advance significantly by pursuing, in as rigorous and as thoroughgoing a manner as possible, the implications of the postulate of direct perceiving. The reason that direct perceiving can be used in the way suggested is because direct perceiving, like organism-environment mutuality and reciprocity, and the persistence of intention over perception-action cycles discussed above, implies a symmetry. The importance of this implication is that, if it happens to be the right symmetry, then the conceptual route to understanding "knowing about" will have been identified. As we have learned so well this century, symmetry dictates design. The idea of constraining experimentation and theory building by symmetries is the ultimate intellectual legacy bequeathed to contemporary and future scientists by Einstein.

Perceiving is a "polyphasic" phenomenon, and the notion that perceiving is direct implies that the various phases of matter involved (mechanical, plasmic, biological, and psychological) must obey certain fundamental compatibility relations (Shaw & McIntyre, 1974). For the required compatibility, not only must laws be invariant within a phase but they must exhibit conjoint invariance across phase boundaries. Direct perceiving implies a symmetry in the structure of the interactions among the laws of matter's different phase. To come to terms with perceiving as a natural state of affairs, therefore, is to understand lawful relations that are invariant over a change in phase. We have no illusions about the difficulty of pinning down the nature of the symmetry principle that fixes the directness of perceiving. It seems to us that neither the data nor the theoretical expertise available at the tail end of the twentieth century is at the level of sophistication required to formulate the intrinsic symmetry of the governing physical laws. To an important degree, contemporary data and theory are not up to the task because of a widespread and historical tendency to treat perception and action as if they were phenomena (1) outside the purview of universal physical principles and well-tried physical strategies, and (2) to be explained by accounts far less abstract, and considerably less general, than those that address motion and change in nonliving material (Kugler & Turvey, 1987; Turvey, 1990a, 1990b). Only by reversing this tendency can the science of the twenty-first century hope to reveal the symmetry that underwrites the perceptual abilities of organisms and the action capabilities that they support. Such will be the charge for the new century's students of cognition who would wish to understand the "knowing about" that is exhibited every summer by the likes of dragonflies in the thickets of New England and by the human observers, like ourselves, who choose to watch and wonder about them.

Acknowledgments.

Preparation of this manuscript was supported in part by National Science Foundation Grants BNS 90-11013 and BNS 91-09880 to Michael Turvey and National Institute of Child Health and Human Development HD-01994 to Haskins Laboratories. The contributions of Claudia Carello to the conceptual content of this paper and to its artwork is gratefully acknowledged.

References

Brooks, R. (1991). Intelligence without representation. *Artificial intelligence*, *47*, 139-159.

Carello, C., Turvey, M. T., Kugler, P. N., & Shaw, R. E. (1984). Inadequacies of the computer metaphor. In M. Gazzaniga (Ed.), *Handbook of cognitive neuroscience* (pp. 229-248). New York: Plenum.

Clancy, (1992). The frame of reference problem in the design of intelligent machines. In K. V. Lehn (Ed.), *Architectures for intelligence (Proceedings of 22nd Carnegie Symposium on Cognition)* (pp. 357-423). Hillsdale, NJ: Erlbaum.

Effken, J. A., & Shaw, R. E. (1992). Ecological perspectives on the new artificial intelligence. *Ecological Psychology, 4,* 247-270.

Fodor, J. (1975). *Language of thought.* New York: Cromwell.

Full, R. J. (1989). Mechanics and energetics of terrestrial locomotion: Bipeds to polipeds. In W. Weiser & E. Gnaiger (Eds.), *Energy transformations in cells and organisms* (pp. 175-182). New York: Thieme Verlag.

Gibson, J. J. (1961). Ecological optics. *Vision Research*, *1*, 253-262.

Gibson, J.J. (1966). *The senses considered as perceptual systems.* Boston: Houghton Mifflin.

Gibson, J.J. (1979/1986). *The ecological approach to visual perception.* Hillsdale, NJ: Erlbaum.

Harnad, S. (1990). The symbol grounding problem. *Physica D*,*42*, 335-346.

Henderson, L. J. (1913). *The fitness of the environment.* New York: Macmillan.

Iberall, A., & Soodak, H. (1987). A physics for complex systems. In F. E. Yates (Ed.), *Self-organizing systems: The emergence of order* (499-520). New York: Plenum.

Johnson-Laird, P. N., Herrman, D. J., & Chaffin, R. (1984). Only connections: A critique of semantic networks. *Psychological Bulletin*, *96*, 292-315.

Kirsch, D. (1991). Foundations of AI: The big issues. *Artificial Intelligence*, *47*, 3-30.

Kugler, P. N., & Turvey, M. T. (1987). *Information, natural law, and the self-assembly of rhythmic movement*. Hillsdale, NJ: Erlbaum.

Kugler, P. N., & Turvey, M. T. (1988). Self organization, flow fields, and information. *Human Movement Science*, *7*, 97-129.

Kugler, P. N., Shaw, R. E., Vincente, K. J., & Kinsella-Shaw, J. (1990). Inquiry into intentional systems 1: Issues in ecological physics. *Psychological Research*, *52*, 98-121.

Lee, D. (1990). Getting around with light or sound. In R. Warren & A. Wertheim (Eds.), *Perception and control of self-motion* (pp.487-506). Hillsdale, NJ: Erlbaum.

Pollack, J. (1993). On wings of knowledge: A review of Allen Newell's *Unified Theories of Cognition*. *Artificial Intelligence*, *59*, 355-369.

Reed, E., & Jones, R. (1982). *Reasons for realism: Selected essays of James J. Gibson*. Hillsdale, NJ: Erlbaum.

Rosen, R. (1991). *Life itself*. New York: Columbia University Press.

Schrödinger, E. (1945). *What is life?* New York: Macmillan.

Sejnowski, T. & Rosenberg, C. (1987). Parallel networks that learn to pronounce English text. *Complex Systems*, *1*, 145-168.

Shaw, B., McGowan, R., & Turvey, M. T. (1991). An acoustic variable specifying time-to-contact. *Ecological Psychology*, *3*, 253-261.

Shaw, R. E., & Alley, T. (1985). How to draw learning curves: Their use and justification. In T. D. Johnston & A. T. Pietrewicz (Eds.), *Issues in the ecological study of learning* (pp. 275-304). Hillsdale, NJ: Erlbaum.

Shaw, R. E., Flascher, O., & Mace, W. M. (1994). Dimensionen der Ereigniswahrnehmung. In W. Prinz & B. Bridgeman (Eds.), *Enzyklopädie der Psychologie, Wahrnehmung, Kognition, Vol. 1* (pp.457-528). Göttingen: Hogrefe, Verlag für Psycholgie.

Shaw, R. E., & Kinsella-Shaw, J. (1988). Ecological mechanics: A physical geometry for intentional constraints, *Human Movement Science*, *7*, 155-200.

Shaw, R. E., Kugler, P. N., & Kinsella-Shaw, J. (1990). Reciprocities of intentional systems. In R. Warren & A. Wertheim (Eds.), *Perception and control of self-motion* (pp. 579-620). Hillsdale, NJ: Erlbaum.

Shaw, R. E., & McIntyre, M. (1974). Algoristic foundations to cognitive psychology. In W. B. Weimer & D. S. Palermo (Eds.), *Cognition and the symbolic processes* (pp. 305-362). Hillsdale, NJ: Erlbaum.

Shaw, R.E. & Turvey, M.T. (1981). Coalitions as models for ecosystems: A realist perspective on perceptual organization. In M. Kubovy and J. Pomerantz (Eds.), *Perceptual Organization* (pp.343-416). Hillsdale, NJ: Erlbaum.

Shaw, R. E., Turvey, M. T., & Mace, W. (1982). Ecological psychology: The consequence of a commit-ment to realism. In W. Weimer & D. Palermo (Eds.), *Cognition and the symbolic processes*(pp. 159-226). Hillsdale, NJ: Erlbaum.

Solomon, H. Y., Turvey, M. T., & Burton, G. (1989). Gravitational and muscular variables in perceiving extent by wielding. *Ecological Psychology*, *1*, 265-300.

Swenson, R. (1989). Emergent attractors and the law of maximum energy production: Foundations to a theory of general evolution. *Systems Research*, *6*, 187-197.

Swenson, R., & Turvey, M. T. (1991). Thermodynamic reasons for perception-action cycles. *Ecological Psychology*, *3*, 317-348.

Tolman, E. C. (1932). *Purposive behavior in animals and men*. New York: Century.

Turvey, M. T. (1990a). The challenge of a physical account of action: A personal view. In H. T. A. Whiting, O. G. Meijer, & P. C. W. van Wieringen (Eds.), *The natural-physical approach to movement control* (pp. 57-93). Amsterdam: VU University Press.

Turvey, M. T. (1990b). Coordination. *American Psychologist*, *45*, 938-953.

Turvey, M. T. (1992). Affordances and prospective control: An outline of the ontology. *Ecological Psychology*, *4*, 173-187.

Turvey, M. T., & Shaw, R. E. (1979). The primacy of perceiving: An ecological reformulation of perception for understanding memory. In L-G. Nilsson (Ed.), *Perspectives on memory research*. Hillsdale, NJ: Erlbaum.

Turvey, M. T., Shaw, R. E., Reed, E., & Mace, W. (1981). Ecological laws of perceiving and acting: In reply to Fodor and Pylyshyn (1981). *Cognition*, *9*, 237-304.

Verschure, P. F. M. J. (1992). Taking connectionism seriously: The vague promise of subsymbolism and an alternative. *Proceedings of the 14th annual conference of the cognitive science society*. Hillsdale, NJ: Erlbaum.

Weir, M. (1985). *Goal-directed behavior*. New York: Gordon & Beach.

Yates, F. E. (1986). Outline of a physical theory of physiological systems. *Canadian Journal of Physiology and Pharmacology*, *60*, 217-248.