The Challenge of a Physical Account of Action: A Personal View*

M. T. Turvey†

This paper is about what I believe is at issue in attempting to bring the analysis and explanation of movement in line with physics and why I think that it is important to make the attempt. There is a small problem. I am not qualified to be a broker of physics. I am an experimental psychologist, drawn to this discipline from physical education some 25 years ago out of a simple desire to understand how humans and animals can move in the ways they do. Why then should I step outside my area of expertise to broach this topic?

The kinds of movements that I had in mind originally—coming from physical education—were of the highly skilled, athletic kind that we see in sport. It was a rude awakening to find out, shortly after beginning graduate studies in experimental psychology and physiological psychology, that the known facts and proposed theories were far removed from providing the type of understanding that I sought. I soon oriented to more mundane movements—walking, running—and to the basic capabilities that underlie them, such as visual perception. This change in orientation, however, did little to relieve my despair with the academic, scientific approach to movement. Regardless of the level of movement coordination, be it simple like walking or complex like performing a hecht in gymnastics or returning a serve in tennis, the available conceptual tools seemed inadequate to the task of explanation.

Especially bothersome to me as a young—and I must confess, very naive—graduate student, was the standard theory of visual perception with which I was supposed to understand how movements are planned and executed. Without going into detail, the central thesis seemed to be that perception began with the outputs of sensory transducers—signals referring to variables of energy—and proceeded, by inference and recourse to memories, to fashion an image or description of whatever it was in the environment at which the person or animal was looking. Two aspects of this theory were particularly irksome to my physical education mentality. One aspect was that it made perception tenuous, gullible, and not really to be trusted. After all, perceptions were arrived at through procedures that could make mistakes and could, in principle, do so regularly. Vision, so construed, seemed terribly ill-suited to the job of providing the basis for controlling movements. How could people and animals move so successfully in environments cluttered with stationary and moving objects, and how could they reproduce skilled acts so reliably, if visual perception, at bottom, was questionable? The other irksome aspect was that, according to this theory of perception, getting a percept was one stage, using that percept to control movement was another, quite separate, stage. With respect to understanding how movements were steered, directed, controlled by perceiving environmental objects and motions,
no gains were to be made in this regard by an account of vision that promised only internal renditions of (more exactly, guesses about) these objects and motions. How could people and animals move so successfully in environments cluttered with stationary and moving objects, and how could they reproduce skilled acts so reliably, if visual perception, at bottom, was logically separate from, and indirectly related to, movement?

Returning to my assumed role as a physics broker, I can now begin, albeit slowly, to let you see why I feel compelled to address movement in physical terms even though I lack the qualifications to do so. Basically, the compulsion arises from the way in which I choose to “resolve” the two questions just posed, the ones that irked me as a naive graduate student. The resolution I go for can be stated succinctly: Perception is direct. Less succinctly, perception is based on the detection of information—of invariant, macroscopic properties of structured energy distributions that are generated lawfully by properties of the environment. Memories, inferences, representations, images, and the like play no necessary role in the pick-up of information, but they are often accompaniments or by-products of the process. With respect to my questions, if there are no intermediary steps of a conceptual or inferential nature, and if the (optical, acoustical, etc.) support for perceiving is grounded in law, then perceiving can be incorrigible rather than gullible, and it can be, therefore, the reliable, objective contact with the surrounding environment that moving people and animals need. That takes care of the first question. Let me now turn to the second. It is not extraordinary, in conversational language, to assert that a person or an animal sees not just objects and events but how to behave with respect to them. This assertion amounts to the claim that possibilities for movement, and properties that bear immediately on the kinetic requirements of a movement (such as torques to be generated, chemical energy to be degraded, etc.), are included among the things that people and animals perceive. Suppose that perceiving is direct; then the possibilities and properties just referred to would be perceived directly and, as a result, what a person or an animal perceives and how the person or animal moves would be connected in the most intimate and secure sense. That takes care of the second question. As I hope will become evident, the two answers assume implicitly conceptions and strategies that one ordinarily associates with a physical perspective on nature. To anticipate, in advocating direct perceiving I am promoting a point of view about living systems that is materialist (without being classical reductionist) and dynamicist (without being dialectical or Whiteheadian, as Bunge [1977] would phrase it).

Direct Perceiving as a Cornerstone and Touchstone of Inquiry

Of course, the “resolution” to the above questions in direct perceiving is not something that I came up with. It is the radical idea of J. J. Gibson (1966, 1979). Now, I should mention at the outset that I have no intention of proving that perception is direct. As you will see shortly, it is not, in my view, an hypothesis to be tested as much as it is a point of departure for understanding some particularly difficult aspects of nature. If you will permit me to revert to the innocence of my early graduate student forays into movement, I will remark that direct perceiving is an elegant notion. Where the perceptual theory that I did not like painted a picture of disharmony between animal and environment, this perceptual theory of Gibson’s renders animal and environment harmonious. To me, Gibson’s picture is the more beautiful of the two. It is simpler and more symmetrical. And because of this simplicity and symmetry it has the noteworthy property of being a theory of perceiving that, unlike its predecessors or contemporaries, does not create epistemological paradoxes.

If one does not choose to prove direct perceiving, then what does one do with it? The answer, I believe, is to use it as the basis for investigating living systems as
"knowing agents"—that is, as systems that know about their surroundings and their capabilities and can act to fulfill intentions. Such an investigation contrasts, as we all appreciate so well, with investigating living systems as just biological systems, or as just physical systems. The reason that I think the notion of direct perceiving should be used in the way suggested is that it is the only view of perceiving that guarantees reliable epistemic contact between an animal and its surroundings. So, even though we are not yet in a position to understand the notion of direct perceiving, I think we have no option but to go with it as the cornerstone and the touchstone of inquiry into knowing agents. Obviously, for perceiving to be direct, certain things will have to be true about living systems and about nature more generally—particularly, I suppose, at the terrestrial scale, but at other scales too. Perceiving directly results from nature being constrained in particular ways. Consequently, we can expect to learn much by pursuing, in as rigorous and as thoroughgoing a manner as possible, the implications of the postulate of direct perceiving.

The reason that I think the notion of direct perceiving can be used in the way suggested is because, as intimated a few lines back, it implies a symmetry. The importance of this implication is that, if it happens to be the right symmetry, then the path to the right theory of knowing agents will have been identified. As we have learned so well this century, symmetry dictates design. In many respects, this strategy to which I am referring obliquely, namely, of letting symmetry guide experimentation and theory building, is the ultimate intellectual legacy bequeathed by Einstein to modern science. The figure below (adapted from Zee, 1986) captures nicely the contrast between two ways of doing science—symmetry lagging experimental investigations and theory building (before Einstein) versus symmetry leading experimental investigations and theory building (after Einstein).

Nobody has been more concerned with the symmetry implied by direct perceiving than my colleague Robert Shaw. Let me try, in relatively few words, to convey some of his thoughts on the topic. Perceiving is a "polyphasic" phenomenon, and the notion that perceiving is direct implies that the various phases of matter involved (shall we
say, mechanical, plasmic, biological, and psychological) must obey certain fundamental compatibility relations. It can be presumed that there are laws that go with each phase; we know for sure that this is true for the mechanical and plasmic phases, and we recognize that biology and psychology have phenomenological laws (concise statements of empirically observed regularities) that may or may not prove unique. For the required compatibility, not only must these laws be invariant within a phase but they must exhibit conjoint invariance across phase boundaries. The upshot is that direct perceiving implies a symmetry in the structure of the interactions among the laws of matter’s different phases.

I will need to introduce a few symbols in order to depict what this symmetry looks like at the level of immediate interest—the level at which animals and people perceive and move. Let \( y_e \) be a property of the environment or a property of the movement of a point of observation relative to the environment. Let \( y_p \) be the perceiving of that property. Let \( i \) be an alternative description of the light at the point of observation that is structured by \( y_e \); \( i \) is a qualitative macroscopic property lawfully determined by \( y_e \). Further, let \( > \) be the symbol for an adjunctive relation in the sense that \( x > y \) reads as “since \( x \) then \( y \),” a statement that holds true only if both \( x \) and \( y \) are true. Finally, let \( \odot \) be the symmetry symbol and let \( \odot \) signify “and.” Now we can express Shaw’s (Shaw & McIntyre, 1974) interpretation of the symmetry implied by (responsible for) direct perceiving as follows:

\[
(y_e \odot y_p) = (y_e > i) \odot (i > y_p).
\]

In words, a symmetry between a property of the environment and the perceiving of that property means: “since the property of the environment is what it is, then the information is what it is” and “since the information is what it is, then the property of the environment perceived is what it is.”

One might now, perhaps, appreciate why it is that I regard perceiving as a problem in physics (that is crying out for a profound solution) and why it is that I have taken the bold step of being a broker of physics. As a first approximation, understanding perceiving is a problem of understanding lawful relations that are invariant over a change in phase. Four clarifications are required. First, the lawful relations in question are primarily of the kind \( (y_e > i) \), and almost all of them remain to be discovered. Second, phase refers to material organization—that of surfaces and multiply reflected light on the one hand and that of biological tissues and processes on the other hand. Third, the symmetry statement is incomplete. There is a dual component that expresses perceiving’s intentionality. I will give the full version of the symmetry subsequently, after a discussion of the challenges that information and intentionality pose for a physical account. Fourth, the symmetry statement merely identifies the entities involved. It is conceptually at some distance from the physical symmetry principle to which it refers.

I have no illusions about the difficulty of pinning down the nature of the symmetry principle that fixes the directness of perceiving. It seems to me that neither available data nor theoretical expertise are at the level of sophistication required to formulate the intrinsic symmetry of the governing physical laws. In largest part, I see this inadequacy of data and theory to be the result of a widespread and historical tendency to treat perception and action as if they are phenomena (a) outside the purview of universal physical principles and well-tried physical strategies and (b) to be explained by accounts far less abstract, and considerably less general, than those that address material motion and change. Only by reversing this tendency can we hope to reveal the symmetry that underwrites the perceiving-acting competence of animals.
Methodological or Strategic Physics

I am hoping that, at this stage of the paper, the following assertion comes as no surprise: I take it that living systems are ordinary physical systems that have “discovered” extraordinary means of using physical principles and laws. Coordinated movements are law governed. Such being the case, physical reduction is implied and required. The question is, what kind of reduction?

Classical physical reductionism will not do. The prospects for explaining epistemic, intentional, and coordinational facts about living systems through classical reductionism are very slim at best and misguided at worst. Classical reductionism is the substitution of the properties at one scale of nature—here, the scale at which coordinated biological movements are in evidence—by the properties at another, putatively more basic, scale. The decisive (but, I think, unacceptable) idea of classical reductionism is that the taxonomy of physical types by which nature is described at its rock-bottom quantum mechanical scale is the taxonomy of physical types by which nature is to be described at any scale.

Fortunately, within the contemporary scene, we can find more than one version of physical reductionism. The version that I like, and the one that I think can do the job, is based on the premise that there is a single set of strategies that nature applies, with equanimity, to each of her scales. These strategies produce, at any given scale, event regularities and morphological objects that are oftentimes unique to the scale. Many of these strategies have been identified and catalogued by physics. Collectively, they provide a repertoire of methods by which nature, at any scale, can be investigated (Kugler & Turvey, 1987).

My working premise, therefore, is that this methodological physics, applied systematically to the phenomena of movement coordination, will deliver a parsimonious, principled account thoroughly consistent with the accounts given of phenomena investigated within the so-called hard natural sciences.

Why Physics Might Resist Examining Coordinated Movements

Before I venture into the methodologies in question, I will address what it is about coordinated movement phenomena that makes them unappealing to physics. (My comments here mirror those of Yates [1987] with respect to the general status of biological phenomena in physical theory.) Foremost, perhaps, is the observation that the spatial-temporal patterning of biological movements are too special for physics. If one is in the business of searching for the overarching principles of nature, then coordinated movements are not the kinds of things to which one would turn with enthusiasm. Coordinated movements are specialized or particularized by their initial conditions, boundary conditions, and constraints. These auxiliary conditions are superimposed upon the general laws and principles to yield the facts of movement coordination. One can think of them as having to be stipulated independently before the laws and principles can be brought to bear on the movement realm. Determining these auxiliary conditions is taken to be the job of “movement scientists,” not physicists.

As problems in physics, coordinated movements might be dismissed as “squalid state physics” (Kadanoff, 1987). On the other hand, as with other examples of complexity in the world around us, coordinated movements raise questions fundamental to the general understanding of physical laws and principles (see Kadanoff, 1987). For example, how do very simple laws give rise to so many diverse and richly intricate structures? Why are such structures so ubiquitous at the ecological scale, that is, the scale of animals and their environments? Why is it that these structures often embody their own kind of simple physical laws?

A commitment to addressing these questions as they apply to coordinated movements imposes particular demands on physics. First, classical ideas in physics...
will have to be applied in novel ways. Second, strict determinism will have to be relinquished in order to embrace the novelty and diversity of movement patterns. Third, evolutionary processes—that is, historical, irreversible processes—will have to be comprehended much more deeply. (These are processes in which (a) the macroscopic dynamics are not time symmetric and (b) the influence of small factors, such as fluctuations, can be magnified significantly, especially at points of bifurcation where the breaking and making of symmetry is achieved more easily.) Fourth, information and intentionality will have to be understood in physical terms. The latter demand, I believe, will be the most challenging. To anticipate the response I will give in these pages, information will be seen as a class of lawfully based, nonkinetic observables opening up the range, and enriching the types, of possible interactions for systems that can link their kinetic states to these observables; intentional contents will be seen as kinds of constraints that particularize the physically lawful movement processes and the informational observables. Both visions are founded on the thesis of direct perceiving (the cornerstone and touchstone of inquiry). I will discuss the conceptual demands of the notions of information and intentionality in some detail below, after giving examples of physical strategies at work in studies of movement.

Major Methodologies and Some Illustrations of Their Application to the Study of Movement

The program of physics is to formulate an account of order, regularity, motion and change through a minimal set of first principles (see Kugler, 1986). Its goal is to identify the symmetries (conservations, universal constants, etc.) and the ordering principles (second law of thermodynamics, Boltzmann's ordering principle, etc.) that combine to predict events. Descriptions of events are carried out by means of certain observations. Then, symmetries are revealed as correlations among descriptions that are invariant from region to region; ordering principles are revealed by changes in the correlations; and the formal expressions of transformations that leave correlations among descriptions unaffected, and those that change them, are what is meant by natural laws.

Let us now see what it might mean to place the account of action firmly within this program. I will choose some examples with which I am reasonably familiar and use them to highlight the notion of strategic or methodological physics referred to above. As far as movement patterns go, these examples are plain and at some remove from the richly patterned movement achievements of animals and humans that we can witness on a daily basis. Nonetheless, the chosen examples are quite sufficient for our purposes. The major strategies that I will try to highlight are drawn from the following nonexhaustive list, where strategies are expressed as questions regarding the control and coordination of movements.

(1) How are the (classical) continuous conservations at work? How do they contribute to the formation of simple dynamical regimes from complex, multiple degrees of freedom systems?
(2) What are the symmetries? Are there new symmetries at work indicating, thereby, new conservations?
(3) What are the symmetry breaking and making mechanisms (producing new structures with new functions permitting new levels of interaction)?
(4) What dimensional and nondimensional scalar constants are at work?
(5) What are the order parameters (that reduce high dimensional state spaces to low dimensional control spaces)?
(6) What is the submanifold of singular states that determines the structure and functional form of a system's behavior?

(7) What archetypal oscillatory regimes are at work, singly and in combination? Are novel oscillatory regimes in operation, made possible by the dependence of biological function on frictional processes?

In what follows I present data and arguments bearing on four general types of movement phenomena. As promised, the goal of these presentations is to provide an impression of how a strategic physics might further the understanding of movement. Given this goal, I have taken the liberty of adopting a tutorial mode of exposition. The consequence is that the discussions are fairly detailed and possibly too detailed for the purposes of some readers. I ask their indulgence. The topics to be discussed are the invariant properties of quadruped gaits, spontaneous transitions in movement patterns, chunking of movements, and the natural bases of action categories.

**Attractors of Steady-state Gaits**

Many movements are rhythmic, as in walking, flying, and swimming. An observer could measure the period of a rhythmic movement, its amplitude and—if the rhythmic movement were executed in conjunction with another rhythmic movement—its phase. These observables and others describe the rhythmic act. A first question might be: What determines the values of these observables? A better first question would be: What determines the values that these observables take most commonly? Phrasing the question in this latter way directs investigation to a rhythmic movement system's "deep structure" (if I may be permitted to borrow a phrase from Chomskyan linguistics)—the states that guide and shape the "surface" behavior of the observables.

Suppose that one were to record the ordinary, preferred periodic times of freely walking quadrupeds of different sizes and shapes (for example, gazelles, lions, giraffes). Regressing the logarithms of these measures of limb cycle times against the logarithms of measures of limb mass and limb length would reveal that cycle time varies as mass to approximately the 1/6 to 1/8 power and as length to approximately the 1/2 power. Further observation would show that these scaling relations are preserved when quadrupeds trot and canter. That is, the increase in speed accompanying change of gait leaves invariant the relation between period and the dimensions of the body (Pennycuick, 1975).

Two additional facts can be noted. First, if log cycle time is regressed simultaneously on log mass and log length, then the mass exponent vanishes and the length exponent stays at 1/2. In one sense this fact is not surprising: biological masses and lengths are correlated (as a general rule, length = body mass^{1/3}) and so one of the two magnitudes is redundant and should disappear in the multiple regression. The difficulty is understanding why the one that disappears should be mass. Second, if the limbs of the various quadrupeds are regarded as compound pendulums convertible into simple pendulum equivalents of length L, then quadruped walking, trotting, and cantering approximate closely the cycle times of a freely oscillating pendulum of length L/2, L/7 and L/10, respectively (Kugler & Turvey, 1987; Turvey, Schmidt, Rosenblum, & Kugler, 1988).

It is not difficult to think of the legs of quadrupeds and bipeds, and the wings of large birds, as hybrid simple pendulum/mass-spring systems. The mass m of a limb can be thought of as concentrated at a distance L from its axis of rotation with a spring of coefficient k attached to the simple pendulum at a distance b from the axis. If allowed to swing freely without damping, the characteristic period \( \tau_0 \) of such a hybrid simple pendulum/mass-spring system (for small amplitudes) would be...
\[ \tau_0 = 2\pi [mL^2/(mLg + kb^2)]^{1/2}. \]

Experiments and computer simulations show that the periodic timing of locomotory type activity is modeled well by this equation (Turvey et al., 1988). The denominator in the preceding equation contains two torsional stiffnesses. When applied to a biological movement system, one of the stiffnesses \( mLg \) is associated with gravity and the mass and length of the limb. The other stiffness term \( kb^2 \) is associated with the elasticity of the body's tissues. I will assume that if the foregoing equation models limbs cycling at their preferred periods, then general principles must be at work governing the assembling of the elastic term over the body's tissues.

Let \( mLg = \mathcal{G} \) and let \( kb^2 = K \). Use of the foregoing equation permits the production of \( \tau_0 \)s for (a) varying pairs of \( m, L \) values constrained by \( L \ll m^{13} \) and (b) relations of \( K \) to \( \mathcal{G} \). Given \( K/G = \) a constant, multiple regression of \( \log \tau_0 \) on \( \log m \) and \( \log L \) reveals that the mass exponent vanishes and the length exponent is \( 1/2 \). With simple regression the mass exponent is \( 1/6 \) and the length exponent is \( 1/2 \). The foregoing equation accommodates the scaling facts of quadruped locomotion. Further, if \( K/G = 1 \), then the equation reduces to \( \tau_0 = 2\pi(L/2g)^{1/2} \), which characterizes walking; if \( K/G = 6 \), and \( K/G = 9 \) then the equation reduces to \( \tau_0 = 2\pi(L/7g)^{1/2} \) and \( \tau_0 = 2\pi(L/10g)^{1/2} \), which characterize trotting and cantering, respectively. It would appear that what makes the periods of a gait cohere across animals of different sizes and shapes is the fact that the elastic restoring torque assembled by each animal, namely \( K \), is the same constant multiple of the gravitational restoring torque associated with the magnitude of each animal, namely \( G \) (Turvey et al., 1988). The ratio of \( K \) to \( G \) defines a relation between macroscopic properties that is invariant over the transformations in size, shape, and differences in phasing details. I think that it is fair to say that quadruped locomotion is organized around well-defined attractor states that may well apply universally at the ecological scale. Any effort to understand how the movement patterns of quadruped locomotion are produced should heed the dimensionless \( K/G \) scalars; they inform about the physical quantities shaping the patterns.

Order Parameters and Order Transitions

Characteristic of quadruped locomotion is the presence of relatively sharp transitions between one gait and another as the speed of locomotion increases. Given that the three major gaits comprise distinctively different phasings of limb activity, the discontinuities in locomotion are transitions among qualitatively distinct movement patterns. Everyday activity is replete with such transitions and it is clear that a thoroughgoing theory of action will have to accommodate them. The question to be posed here is whether or not physics can be of help. In answering the foregoing question I will outline two related aspects of the general physical strategy for widening the understanding of discontinuities in a system's behavior. One aspect is the identification of the basic variable in the description of a transition; the other aspect is the inventory of properties characterizing the dynamic underlying a transition.

Although order is induced in physical systems through a wide variety of means, phase transitions exhibit considerable uniformity. The implication is that the order, newly evolved through a phase transition, might be expressed in a standard way. To achieve this standard formulation, a macroscopic quantity, called an order parameter, is identified for each physical system as the variable that (a) simplifies the description of the transition because it is assembled from the most relevant quantities, which tend to be few in number, and (b) expresses the extent of the system's order during the transition. In a liquid-gas system the order parameter is density. This single-component quantity satisfactorily captures the spatial order of the system. In contrast, superfluids require a two-component quantity—namely, a
wavelike periodic space variable—to capture their spatial order and act, thereby, as the order parameter.

I usually find that a well-worked example of Landau and Lifshitz's (1980) helps to fix this idea of an order parameter, at least in its most basic form. The completely ordered copper-zinc alloy (brass) is a cubic lattice with the zinc atoms at the vertices, say, and the copper atoms at the centers of the cubic cells. Disordering occurs as the copper and zinc atoms change places, that is, when a non-zero probability exists of finding either atom type at every lattice site. The lattice's symmetry remains unchanged, however, as long as the probabilities of finding zinc at the vertices and copper at the centers are unequal. With equality, the crystal's symmetry is raised and a second-order phase transition has occurred. The raising of the symmetry is in terms of more transformations over which its configuration is left invariant; to be precise, more translations among the lattice planes. A quantity can be defined that is a function of the probabilities of finding a copper atom and a zinc atom, respectively, at any given lattice site:

\[ \mu = \frac{(P_{\text{Cu}} - P_{\text{Zn}})}{(P_{\text{Cu}} + P_{\text{Zn}})}. \]

This quantity \( \mu \) is 1 when the atoms are in the right place (lower symmetry, more order) and 0 when the spatial distribution is 50/50 (higher symmetry, less order). \( \mu \) is the copper-zinc system's order parameter; it wraps up in a one-dimensional space the very many degrees of freedom comprising the alloy's microstructure.

It is important to underscore that an order parameter is (a) a specific feature of a given system, and (b) may be composed of several quantities (as indicated in the brass alloy example and the liquid-gas vs. superfluid contrast). This means that a system's order parameter will not always be immediately obvious and cannot be ascribed in an ad hoc manner. (For open systems this ascription problem is worsened by the fact that there may be several order parameters, each with several components!) At all events, for the second-order phase transitions exhibited by isolated physical systems, the sought after unified formulation is achieved through a joint consideration of the dimensionality of the physical system \( (d) \) and the dimensionality (number of components) of the order parameter \( (n) \). Systems with the same \( d \) and \( n \) behave in the same way even though they may be materially (microscopically) quite different.

Returning to the locomotory gaits, the phase relation among the limbs is a macroscopic variable that provides a simple and efficient description of the spatial order of the locomotory system. Phase, therefore, is a suitable order parameter, particularly when the system is reduced to limbs of the same girdle. Empirical work bears out this supposition, but before examining it we need to address the other aspect referred to above, namely, the hallmark observables of the physical conditions producing behavioral discontinuities.

A useful simplification is that the systems of interest are governed by a smooth potential function \( V(x; c) \) where \( x \) is the system's order parameter and \( c \) is a control parameter that can affect \( V(x) \) qualitatively. The equilibria \( x(c_{\text{critical}}) \) of such systems (referred to as gradient systems) are then defined by \( \nabla V(x; c)/dx = 0 \). (The number of order and control parameters can be greater than one.) The simplification lets us think of behavioral discontinuities as occurring in systems for which the equilibria are changed (dissolved and created) by changes in the control parameter. It lets us see that even though the dynamic underlying a system's behavior is continuous, discontinuities in behavior can arise nonetheless. As an equilibrium dissolves, stability is lost and a transition to a new equilibrium results. Now, having made this simplification and developed the image of "losses of stability precipitating transitions," I wish to note that the presence of critical points in a smooth dynamic...
ushering in discontinuity is recognizable by a set of criteria that hold regardless of the actual make-up of the system.

The criteria are the following (Gilmore, 1981): (a) *modality*, meaning that the system has two or more distinct physical states in which it may occur; (b) *inaccessibility*, meaning that the system has an equilibrium state that is unstable (as when a marble rests at the top of an inverted bowl, or a pendulum is vertical with its bob above the axis of rotation—very small perturbations will dislodge them); (c) *sudden jumps*, meaning that a slow change in the control parameter may lead to a relatively rapid change in the order parameter; (d) *divergence*, meaning that two nearby trajectories in the space of the control parameter may lead to widely divergent final values of the order parameter; (e) *hysteresis*, meaning that a sudden jump \( x_i \) to \( x_f \) and its reciprocal \( x_f \) to \( x_i \) do not occur at the same values of the control parameter; (f) *critical slowing down*, meaning that subsequent to a perturbation, the time taken by the order parameter to return to its preperturbation value increases as the transition point is approached; (g) *anomalous variance or critical fluctuations*, meaning that the variance in the order parameter may become large as the transition point is approached.

A number of the preceding criteria have been observed by Scott Kelso and colleagues (e.g., Kelso, Scholz, & Schöner, 1986; Scholz, Kelso, & Schöner, 1987) in a paradigm in which a person is required to oscillate the two index fingers (or two hands) at the same frequency. The phase relation, as noted above, is the order parameter; frequency is the control parameter varied by a metronome that the person tracks. Results show that there are only two steady states: in phase (homologous muscle groups contracting simultaneously) and antiphase (homologous muscle groups contracting in an alternating fashion). With increasing frequency, antiphase switches rapidly to in phase. In phase, however, does not switch to antiphase, and the antiphase-to-in phase transition is not reversed by a reduction in frequency. Further, the order parameter exhibits critical slowing down and, if the conditions of the so-called delay convention are in effect, then the order parameter exhibits critical fluctuations. These conditions are that the fast time scale associated with the relaxation back to antiphase is notably less than the time scale of change in the control parameter, which, in turn, is notably less than the slow time scale associated with the passage from antiphase to in phase. Order parameter fluctuations do not anticipate the sudden behavioral change when the slow time scale is less than the time scale of the control parameter (the conditions of the so-called Maxwell convention). In sum, the experimental evidence suggests that the comparison of phase transitions in physical systems and behavioral discontinuities in movement systems may be more than mere analogy.

Importantly, the same behavioral transition, exhibiting many of the same criterial properties, has been observed when two limbs are connected optically between two people rather than anatomically within a person (Schmidt, Carello, & Turvey, 1987, in preparation). In the experiments in question, two seated people each oscillated a leg with the goal of coordinating the two legs 180 degrees out of phase or in phase (0 degrees) as the frequency of the movement was increased. To satisfy the goal, the two people watched each other's lower leg. In both the within-person case and the between-person case the phenomenological description of the coordinated movement pattern, and of the change in the coordinated movement pattern, are the same. The two cases involve the same relation among the same observable quantities. As such, one and the same dynamics can be used to model phenomenologically the differential stability of the two coordination modes, and the phase transition between them.

I ought to emphasize that the two cases of phase transition do differ, of course, on many dimensions of description. Most notably, they differ in the populations of
neurons involved (the nervous systems of two people vs. the nervous system of one person; using vision in between-person coordination vs. not using vision in within-person coordination). That this dramatic difference in neural substrate did not affect the major qualitative features of the phase transition phenomenon suggests the possibility of an order parameter dynamics that applies equally to both neural settings because the interactions are only superficially different. In abstract yet quantifiable dynamical terms, anatomical and optical connectives between rhythmic movements appear to be identical.

Although I have reported the movement transition data in terms of changes in an underlying smooth dynamic analogous to a potential (e.g., Schöner, Haken, & Kelso, 1986), another conception is possible. The transition from antiphase to phase in the within-person and the between-person cases might be linked to a "threshold nonlinearity" (Kugler, 1986). Let me explain. It is quite likely that the observable involved in the interaction between the oscillating limbs is informational (a point to be expanded upon below) raising, thereby, the possibility of perceptual resolution limitations at work in the fashioning of the transition. On this argument, the antiphase organization collapses at the perceptual limit on resolving the antiphase motion—an argument that is more easily comprehended, perhaps, in the context of optically based, between-person coupling.

The ubiquity of threshold nonlinearities in the design of biological systems suggests that they may well function as a general symmetry breaking mechanism (Kugler, 1986). At critical flow rates, biological components may reach their thresholds at the same time and suddenly, synchronously, change state. The decisive idea here is that of synchronization occurring among biological components not because of connections or shared instructions but because of shared similarities. To my mind this is an interesting idea with obvious ramifications for the understanding of spontaneous changes in coordinated movement patterns.

Conservations and Unitizing

A major problem in understanding biological movements has to do with the formation of units or chunks. Movements usually involve many body segments that are free to vary independently of one another to a greater or lesser degree. In a so-called skilled or coordinated act, however, many relatively independent segments of the body function together, giving the appearance of a homogeneous, integrated, structural unit.

I find certain kinds of data very useful to conceptualizing the movement unitizing problem in physical terms. I have in mind the rapid compensatory adjustments to an ongoing coordinated act that are at some spatial remove from the site of the perturbation (e.g., Bernstein, 1967; Kelso, Tuller, Bateson, & Fowler, 1984; Marsden, Merton, & Morton, 1983; Saltzman & Kelso, 1987). Although the adjustments are witnessed in movement organizations that are assembled temporarily to satisfy particular momentary intents, the rapidity and remoteness of these compensations give the impression of rigid, reflexive-like, long-range interconnections among the involved neuromuscular components. Physically speaking, the impression conveyed is of a cooperativity preserving its macroscopic steady state (say, a stress-strain distribution) through systematic adjustments at the atomistic level. A physical cooperativity assembled over many "atomistic" components exhibits long-range correlations resulting from transport processes that link or couple the atomisms of a field displaced from equilibrium to the distribution characteristics of the field's conservations. I think that this physical image of movement units and their assembly is worth pursuing. More specifically, I would like to explore the idea that one of nature's general strategies—the "assembling" of cooperative states on the basis of conservational requirements—features prominently in the coordination of human and animal rhythmic movements (Kugler & Turvey, 1987).
Let us consider again the mode of rhythmic movement organization that typifies terrestrial mammalian locomotion. For a given speed and gait, each limb is raised and lowered with respect to gravity, with the raising and lowering repeated at regular intervals. The individual step cycle is a pendular, clocking mode of organization (Kugler & Turvey, 1987). To examine the pendular, clocking behavior of a single limb experimentally, a weighted pendulum is held in one hand and made to oscillate by rhythmic movements of the wrist joint. The subject is instructed to swing at the most comfortable tempo. For different weighted pendulums (different shaft lengths, different added masses) the person settles at different tempos. To examine the pendular, clocking behavior of the two limbs, a person holds two pendulums, one in each hand, and swings both simultaneously at the wrists. The two pendulums can be swung in phase (0 degrees difference) or out of phase (180 degrees difference), resembling the organization of symmetric and asymmetric gaits, respectively. Whatever the phase relation, the person is instructed to swing both pendulums at the same tempo, and to do so comfortably. For different pairs of weighted pendulums the person settles at different, common tempos.

Consider the overt material composition of the systems in question. A wrist-pendulum system is a compound pendulum. There are three masses rotating about a point in the wrist joint, namely, the mass of the pendulum shaft or rod, the mass of the added weights, and the mass of the hand. The distances of the centers of these masses from the common point of rotation are not equal. Nevertheless, the total mass of a wrist-pendulum system can be characterized as concentrated at a single distance from the point of rotation. This characterization identifies single mass and single length quantities for a wrist-pendulum system. Most importantly the characterization extends to two coupled wrist-pendulum systems. That is, the total mass of two wrist-pendulum systems, coupled to oscillate at the same tempo, can be characterized as a single point mass at a distance from a single "virtual" point of rotation. The characterization is, most obviously, an expression of unitizing. I wish to show that it rests on the equivalence, by conservational criteria, of compound and simple pendulums. What follows is somewhat pedantic and old hat; but bear with me because it lets me make a specific case for the link between the conservations and unitary movement processes.

A simple pendulum is a particle of mass \( m \) suspended from a weightless string of length \( L \), moving in a vertical plane. If the position of the mass is determined by the angle \( \theta \), then the equation for tangential motion is

\[ -mg\sin\theta = mL\frac{d^2\theta}{dt^2}. \]

Cancelling the mass \( m \) yields:

\[ \frac{d^2\theta}{dt^2} = \frac{g}{L}\sin\theta. \]

A compound pendulum is a rigid body hinged about a horizontal axis not passing through its center of mass, and acted upon by its own weight as an external force. In contrast to the simple pendulum the constituent particles of the compound pendulum are at different distances from the axis of rotation and exhibit different motions and accelerations. In the simple pendulum the mass is concentrated at a single point, that is, there is a single mass particle at a single distance from the point of rotation exhibiting a single motion and acceleration. Consider the compound pendulum acted upon by its weight \( W \) through its center of mass at a distance \( h \) from the axis \( O \). For the displacement \( \theta \) from the vertical position of equilibrium, the motion about \( O \) given by the moment equation is:

\[ I_o \frac{d^2\theta}{dt^2} = -Wh\sin\theta, \]

where \( I_o \) is the moment of inertia about the axis \( O \). On rewriting,

\[ \frac{d^2\theta}{dt^2} = (Wh/I_o)\sin\theta = -(mgh/I_o)\sin\theta. \]
Comparing the last equation with \( \frac{d^2\theta}{dt^2} = -(g/L)\sin\theta \) reveals that the motion \( \theta \) of a compound pendulum is identical with the motion \( \theta \) of a simple pendulum of "equivalent" length \( L_e \), if

\[
L_e = \frac{L}{m}.
\]

That is to say, the compound pendulum is "replaceable" by a simple pendulum without change of behavior (within an appropriately restricted set of circumstances). The equivalent simple pendulum is an abstraction or subsystem (Rosen, 1978) of the compound pendulum. It ignores aspects of the original system. In so doing, however, it allows the behavior of the original system to be "approximated," over some range of conditions, by means of a simpler system. The transformation from compound to simple pendulum is, in effect, a *symmetry operation*. One description replaces another, leaving particular behavioral properties invariant (Rosen, 1978). The foregoing identifies a general physical strategy. I want to establish that it has implications for the problem of unitizing biological movements.

Let me discuss the nature of the transformation a little further. The conversion from compound to simple pendulum reduces a material body oscillating about an axis to a point mass oscillating about an axis. One can imagine the material body to consist of many "micro" simple pendulums, that is, many material particles in pendular motion. Each "micro" simple pendulum, if allowed to oscillate freely alone at the same distance from the axis, would have its own period of oscillation. Because of the rigid connections among the parts of the material body, however, the whole body oscillates, as a compound of "micro" simple pendulums, at a single determinate period. What the transformation defines is the one simple pendulum that exhibits this same period of oscillation. In other words, the compound to simple pendulum transformation replaces many point masses in pendular motion by one point mass in pendular motion.

It is most important to note that the principle behind this many systems-to-one system transformation is the conservation of energy. The transformation and the principle behind it were first articulated in the seventeenth century by the great Dutch scientist Huygens (Mach, 1893/1960). We should express the transformation, therefore, as follows:

\[
C(S) \rightarrow (S'),
\]

where \( C \) is a *conservation-based symmetry operation*, \( S \) refers to system, and \( S' \) refers to subsystem. Elaborating on the latter notions of system and subsystem, if a natural system is defined by its states, its observables, and its interactions (dynamics), then a subsystem can be defined by a subset of those states and/or observables and/or interactions (Rosen, 1978). Different kinds of subsystems are possible, therefore. What they have in common is the feature that the passage from system to subsystem shrinks the system's interactive capabilities.

I will now collect the foregoing arguments and try to identify specifically how it is that the conservation-based transformation \( C(S) \rightarrow (S') \) bears on the unitizing problem in wrist-pendular movements. To repeat my earlier remarks, a left or right wrist-pendulum system is a compound pendulum. The various masses (rod, added weights, hand) are connected through a pattern of mechanical forces. Further, a pairing or coupling of wrist-pendulum systems can also be conceptualized as a compound pendulum, although not in the ordinary sense. Because the various masses are distributed over different links of the body, the connection among them is achieved only partly through mechanical forces. It is a simple matter to demonstrate the absence of a completely rigid, mechanically enforced connection. When the subject is not rhythmically moving the two systems together but merely holding them in a resting posture, a displacement of one or more of the masses of the right wrist-pendulum system is not at the same time a displacement of one or more of the
masses of the left wrist-pendulum system, and vice versa. A connection of sorts, however, must exist between the two systems if they are to move together at a common tempo and at a given phase. This connection is realized, of course, through the nervous system, through a pattern of neural processes. In conceptualizing a pair of wrist-pendulum systems as a compound pendulum it is recognized that the compounding of the left set of masses with the right set of masses is mediated neurally; it is not mediated mechanically.

The upshot of the preceding is that a single wrist-pendulum system and a double wrist-pendulum system, despite their many differences, can both be represented by a single observable, namely, equivalent simple pendulum length. The supposition is that this observable, derived from the conservation-based symmetry operation, captures the dynamics of both single and double systems with respect to periodic timing. Such being the case, a multiple regression conducted on the periods of single and double systems with respect to the continuous variable of simple pendulum length and the categorical variable of system size, or biomechanical degrees of freedom (one vs. two), should find that virtually all of the variance in the dependent measure is accounted for by length and that none is accounted for by degrees of freedom. Analysis of available data (Kugler & Turvey, 1987) conducted in the foregoing manner confirm the expectation; the single vs. double contrast is invisible. We have understood for some time that the acting animal is sensitive to the whereabouts of its center of mass even when this center is repositioned by the uneven distribution of added weights. (The center of mass description comprises a subsystem in the sense above, and is defined through the conservation of linear momentum.) The present analysis extends this traditional understanding by suggesting that the acting animal is also sensitive to the whereabouts of the center of oscillation associated with parts of its body.

I would conclude, therefore, that a case—albeit simple and of limited scope—can be made for entertaining the notion that unitary movement processes may be founded on general physical principles, especially the symmetry operations rooted in the conservations. At least it is an idea worthy of further consideration.

Optical Nondimensional Scalar Constants

The major nondimensional criteria or similitude criteria in physical theory and engineering practice are assembled from laws. The laws in question are those governing the phenomenon of interest. Thus, the Reynolds Number \( \text{Re} = \frac{v e}{u} \) (where \( v \) is the characteristic velocity of the fluid for the given problem, \( e \) is the characteristic linear dimension, and \( u \) is the kinematic viscosity of the fluid), which applies to streaming viscous fluids, can be characterized as the ratio of inertial to viscous forces. Fluid systems governed by these laws are similar if and only if the corresponding dimensionless Reynolds Numbers are numerically equal. Dimensionless numbers like the Reynolds Number are referred to generally as principal \( \pi \)-numbers. Rarely are they constructed from more than two governing laws.

The ratio-of-forces perspective on \( \pi \)-numbers is useful in two notable ways. First, it helps us to understand that similarity of two systems means that the forces in question pattern identically even though they may be of very different magnitudes in the two systems. Second, the perspective helps in understanding the behavioral discontinuities of physical systems of the kind discussed above. At some patterning of forces the phenomenon in question is no longer maintainable. One behavior gives way dramatically to another. For example, laminar flow becomes turbulence as velocity is increased and the balance of the two force structures gives way to the dominance of one (inertial). The transition is indexed by a critical value of the
Reynolds Number. In the terms used in a preceding subsection, the Reynolds Number is a control parameter.

The critical value of a principal \( \pi \)-number indexes a nonlinear (catastrophic) change in the relation between forces. It is a convenient representation of a natural boundary making process where the boundary in question is defined between qualitatively different kinetic states. Philosophers and psychologists might perhaps see a rudimentary form of categorization in the distinguishing of physical states of affairs by a critical \( \pi \)-number. At least I would hope they do because, for me, a significant aim of the ecological approach is the discovery of principled, nonsubjective grounds for the major category of action; critical \( \pi \)-numbers, I believe, provide a methodology for fulfilling that aim (see Warren, 1984; Warren & Whang, 1987).

A number discovered by David Lee (e.g., Lee, 1980) makes my point rather nicely. One of the major requirements of successful action is the control of collisions (Gibson, 1979; Kugler, Turvey, Carello, & Shaw, 1985). A point of observation approaching a substantial surface on a rectilinear path generates a dilating optical solid angle. The apex of the optical solid angle is at the point of observation. Its base is a closed optical contour projectively related to the face of the substantial surface. The inverse of the relative rate of dilation is a (now well known) quantity called \( \tau \) that is specific to the time that would elapse before point and surface contact if the current conditions persisted. (By “current conditions” I mean “speed” and by “speed” I mean the “configuration of forces” moving the point of observation given that the observation point will, in real situations, be occupied by the occular system of an animal.) A person or animal intending a gentle collision with the surface would want to know whether or not the current forces are such that forward momentum would be dissipated satisfactorily by the time the surface was reached. This question about the appropriateness of current forces with respect to a pending encounter must be answered in terms of the properties of current optical structure. Analysis reveals that the boundary between the categories of gentle and violent collisions is marked by a critical value of the rate at which \( \tau \) changes. If \( d\tau /dt \geq -0.5 \) then the collision will be gentle; if \( d\tau /dt < -0.5 \) then the collision will be violent.

Because \( \tau \) is a time, its first derivative with respect to time is dimensionless. Which is simply to say that the Lee Number is a \( \pi \)-number. It is a different kind of \( \pi \)-number, however, than the Reynolds Number, and the other principal \( \pi \)-numbers familiar to physics. Although the Lee Number refers to a qualitative distinction in kinetic states, no kinetic terms (no forces, no masses) are involved in its assembly. The Lee Number is an optical \( \pi \)-number derived from noninertial, kinematic properties of optical flow at the ecological scale. An educated guess is that the Lee Number is paradigmatic of the dimensionless scalars exploited in action—as a general rule these quantities (that await our discovery) will be kinematic, not kinetic, in origin.

Another example of a kinematically derived \( \pi \)-number providing a reliable basis for controlling action categories comes from the study of the conditions under which successful catching is possible (Todd, 1981). A projectile moving parabolically in the observer’s sagittal plane can be described with the aid of two \( \tau \) values. \( \tau _h \) is specific to the time elapsing before contact with the horizontal plane through the point of observation; \( \tau _v \) is specific to the time to contact with the vertical plane through the point of observation perpendicular to the projectile’s trajectory. The ratio \( \tau _h /\tau _v \) is a dimensionless number (I call it the Todd Number) with a critical value of 1. When the ratio is 1, the projectile will contact the point of observation. A value above 1 specifies a landing ahead of the point of observation, a value below 1 specifies a landing behind. The action categories of stay put, charge ahead, or retreat,
in order to intercept the projectile, are thereby specified optically (Turvey & Carello, 1986).

In identifying the dimensionless numbers of the ecological scale we develop an appreciation of the natural seams in the structured energy distributions ambient to animals that bear directly—and in a principled way—on the parsing of action. I expect that many such natural seams will eventually be discovered, and a great many of the fundamental action categories thereby understood in natural, law-based terms. I hasten to add, however, that there is as yet no well-defined strategy for their discovery.

I am hoping, of course, that the four topics just discussed convey the sense and purpose of an approach to the patterning of biological movements that would ground the exploration of such matters in general physical strategies and their explanation in general physical principles. Let me now move on to what are easily recognized as central but elusive concepts in the theory of movement, namely, information and intentionality, and the challenges to which they give rise.

The Challenge of Information

It is quite likely that the reader, having read this far into my personal view, will be of the impression that I am simply advocating uncritical recourse to the available methods of physical inquiry in order to generate acceptable accounts of coordinated movements. The current section should dispel this impression. The centerpiece of a thoroughgoing physical account of action is information. Unfortunately, there is no physical theory of information. This claim may seem odd, given the ubiquity and grand successes of statistical information theory. But the fact remains that the received theory of information in physics is a phenomenological theory of such generality that it disregards the physical states of affairs defining informational interactions between a system and its surround. Questions of the following kind are rarely, if ever, entertained: What kinds of structures carry or contain information? What kinds of energy forms and energy quantities are involved? What are the physical conditions for generating and detecting information naturally? How is information connected to dynamics? Peter Kugler and I contend that a physical account of coordinated movements will require a physical theory of information, and that the motivation for such will have to come from the study of movement itself (Kugler & Turvey, 1987).

The problem is that the concept of information in physics is wrapped up with the less pertinent demands of communicating and representing physical situations. Shannon's now classical measure, for example, indicates the minimum equivalent number of binary steps by which a given representation may be selected from an ensemble of possible representations. Other measures speak to the informational requirements for constructing a representation (MacKay, 1969). Let me give an example of the use of information measures in physics. A contemporary and busy area of application is the theory of chaotic behavior/strange attractors. There exist formally deterministic systems for which it is the case that trajectories emerging from nearby initial conditions diverge exponentially. Because of this dramatic sensitivity to initial conditions, any ignorance about apparently insignificant digits embraces in time the significant digits, leading to unpredictable (chaotic) behavior that cannot be avoided by making more precise initial measures. Consequently, the quantity of information needed to represent a trajectory in a particular time interval consists of the information needed to characterize the trajectory at the start of the interval and the information required to offset the ignorance “leaking in” at a constant rate due to the ignorance about digits that were insignificant at the outset (Grassberger, 1986). In the foregoing example, as in many others from physics, information can be interpreted comfortably as the reduction in uncertainty.
I find the way in which the concept of information is defined and used in physics to have limited bearing on the perceivings and actings of animals. The most generous reading is that it is a concept befitting perception and action considered as discrimination (crudely speaking, it addresses "what something is not but might have been"), and that is far from adequate. The perception of the properties of places, objects, events, and ongoing actions is more fundamental than the perception of the differences among them. Controlling and coordinating acts in ordinary, cluttered surroundings demand information in the sense of information about something, information specific to something; that is, information of a kind that permits the perception of something, as Gibson (1966, 1979) would put it. The point is that conceptions of information that address how to distinguish among and how to represent propertied things are inconsequential if they are not nested within a conception of information that addresses how there can be awareness of those propertied things in the first place.

How can this desideratum be fulfilled? Gibson's (1966, 1979) answer, expressed in Shaw's symmetry statement \( (y_i > i) \cdot (i > y_i) \) and identified a number of times in my remarks above, is to relate the notion of information to lawful regularity. (Consonant with the major theme of this paper, direct perception is being brought to bear as the touchstone of conceptions of information.) It is now appropriate for me to consider this answer in more detail. At the ecological scale, the systems of interest—living things—are immersed in energy distributions. Notable among these ambient energy distributions are those for which the mean energy content is extremely low relative to the energy associated with animals, for example, light distributions ambient to a path of observation traversed by a locomoting animal. The mass term can, therefore, be suppressed effectively in the descriptions of these energy distributions as they bear on the control and coordination of movement. The descriptions are of the spatio-temporal structure—that is, the adjacent and successive order—that is imposed on these ambient 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.). What I would call the ecological conception of information is founded on the assertion that invariant relations exist between layout properties of general significance to the governing of activity and macroscopic, noninertial properties of structured ambient energy distributions.

Let me state succinctly the three decisive ideas behind the ecological conception of information, as Peter Kugler and I understand it (Kugler & Turvey, 1987). First, alternative descriptions in macroscopic kinematic (built from the dimensions of length and time) and/or geometric (built from the dimension of length) and/or spectral (built from the dimension of time) terms can be given of the low-energy distributions enveloping animals. Thus, for example, the observable \( \tau \) identified above is a macroscopic spectral property; for movement of a point of observation with respect to any ordinary terrain, densely cluttered with objects, a \( \tau \) field will be defined. Second, these alternative descriptions are law based and, thereby, determinate. Third, these alternative descriptions do not cause the movements of animals, which are intentional, but they are wholly constraining of them. Because information is determinate, intentional activity can be conducted in a reliable manner. The strength of the ecological conception of information from the perspective of physical theory is that it identifies information as (a) an aspect of ontology close to (within the reach of) dynamics and (b) as a rich class of new observables permitting interactions beyond those permitted by the observables (notably, forces) previously identified in physical theory. Physical theory will be challenged by the task of incorporating these nonkinetic informational observables in a self-consistent manner. But it seems to me that the larger concerns of embracing...
biology by physics demand such coherency. In this respect, a central concern will be the development of a physical understanding of how informational observables function to constrain kinetic observables, such as the force structures produced in the performance of actions (see Warren, Young, & Lee, 1986). At all events, it should be clear that I envisage the inclusion of information relevant to movement as requiring a radical extension of physics. Movement science would not so much be absorbed by physics as physics would be enlarged by movement science (in paraphrase of Rosen, 1978).

The ecological conception of information has two coordinated aspects that I ought to underline. One is lawfulness; the other is specificity. I take a law statement as referring to an invariant relation between properties. In approximate terms I take the specificity aspect to read: Because optical property $o$, say, is generated lawfully (invariantly) by layout property $e$, then $o$ specifies $e$. Lawful generation and specification together define the ecological conception of information.

Let me now concentrate on the fact that an invariant is relative, because it has important implications for the functioning of information observables. An invariant can only be defined with respect to particular transformations. By definition, therefore, relations between properties can differ in terms of the number and kinds of transformations over which they are invariant. In physics, lower and higher symmetries are distinguished. A higher symmetry is an invariant relation defined with respect to very many transformations; it is said to be a situation of lower order because far fewer constraints are involved. Given how information is defined ecologically (in terms of invariant relations between properties), there will be a number of information types or symmetries of differing order. The higher symmetries (lower order) are those that I expect to be associated with the control and coordination of very general movement capabilities such as posture and locomotion. (Whenever, wherever, and however a point of observation moves with respect to the surrounding layout, a global optical flow is defined specific to the fact of observer movement [Gibson, 1966, 1979; Turvey & Carello, 1986]. Global optical flow is an extremely high symmetry, potentially exploitable by all creatures with eyes.) The lower symmetries (higher order) are those that I expect to bear on the control and coordination of more particular and specialized skills. This implied continuum of invariantly related properties suggests that movement capability will depend on the order of symmetry that can be detected. For sensitivity to a given information type, exposure to the relevant transformations is required. The lower the symmetry, the fewer the relevant transformations, and, quite possibly, the lower the probability of encountering them and becoming attuned to the invariant. Thinking in terms of this continuum might help in the understanding of differences between and within species with respect to the complexity of exhibited movement patterns. In a larger perspective, namely, from the point of view of a physics of movement, the continuum implies a metric awaiting careful formulation.

The Challenge of Intentionality

Most students of movement, it seems to me, regard intentional content as the focal problem. Surely, the outstanding feature of biological movement patterns is their directedness towards objects and goals—the fact that they are, more often than not, conducted with purpose. In the case of humans it is plainly true that many coordinated activities follow from a simple desire or wish to do something in a certain way. When a skilled act is produced without much forethought, or none at all, a spectator may remark that it was done "instinctively" or "out of habit" in order to convey the sense of a transfer of responsibility for the act from consciousness to some other source of control. In many respects, discussions of, and proposals for, motor programs and motor plans are oblique references to intentional content. The general idea is that intentions and sub-intentions (programs as hierarchic in
structure) can be conceptualized as sets of instructions or commands in the form of symbol strings (if one is inclined toward von Neuman machines) or in the form of weightings among connected processing units (if one is inclined toward connectionist machines). In largest part, research in movement science—of both the neural and cognitive variety—is aimed at identifying the details of these command structures.

I have no desire to see intentional content dislodged from the pedestal onto which it is placed by students of movement. I do desire, however, to see intentional content brought systematically within the purview of the natural sciences. To this end, I think that we should treat intentional contents as nonholonomic constraints (approximately speaking, circumstances that restrict behaviors without deleting degrees of freedom). Realist ontology equates possibility with lawfulness. Actuality is what follows from the combination of laws and circumstances. Because of laws, certain actions are possible; because of the juxtaposition of intentions and other auxiliary conditions, those actions are actualized. The key idea that I wish to pursue is that intentions provide an extraordinary class of circumstances harnessing laws in highly particular ways to produce highly particular functional organizations.

The extraordinary nature of intentional content must be noted. There are two major aspects, one familiar and one unfamiliar. I will deal with the familiar aspect first. Given an intention to do y, y usually follows (if conditions permit). An intention seems to relate causally to behavior, although it is not causal in the ordinary physical sense of that term. One notable departure is that an intentional content not only identifies the conditions that satisfy the intent but it also brings about these satisfying conditions. Ordinarily, one likes to identify causes independently of their effects. For intentions, antecedent and subsequent descriptions conflate. It has been scientific custom to interpret such anomalies—the failure of intentional content to satisfy agreed-upon conventions for causality—as sufficient reason to deny intentional causation. This has led to extraphysical interpretations of intentional content and an enduring tendency to construe causation in such a way as to prohibit the inclusion of intentions. In order to break the deadlock I think that we need a concerted effort to (a) naturalize intention and (b) intentionalize causation (Kugler & Turvey, 1987). That is, it will become necessary, on the one hand, to detail how intentional content fits into the context of natural laws and, on the other hand, to reconceptualize the notion of causation taking intentionality as the departure point.

Discussions of directedness toward objects (the standard way in which intentionality is construed) are usually conducted at a level of abstraction that avoids addressing what it means precisely for such directedness to be achieved. Making the requirements for achievement concrete will, I believe, provide a rich basis for understanding intentionality in natural terms. Consider the implications of the following example of directedness. To enter the water smoothly, a gannet diving for a fish must fold its wings prior to contact with the water. Wing retraction is initiated at a particular value of $\tau$ (Lee & Reddish, 1981). To alight gently on the water, the gannet must spread its wings and decelerate prior to landing. Wing extension is probably initiated at a different value of $\tau$ than wing retraction. The bird's intentional contents—the goals of the gannet's actions, if you will—are tantamount to selections of criterial values of a lawfully generated optical property. There are many circumstances in which humans synchronize their acts with environmental events in a skilled manner, suggesting that the individuation of $\tau$ values by intentionality is of wide scope. A general formulation of this aspect of intentionality reads as follows: To intend act $a$ is to select/detect the marginal value $v$ of $i$, that is, the value of the property of the structured energy distribution that satisfies the requirements of $a$.  

*Challenge of a Physical Account of Action*
The foregoing introduces the second, less familiar aspect of intentionality, namely, as a specific relationship to or harnessing of invariant relations between substantial properties. I think that we have to understand this aspect as part and parcel of the symmetry responsible for direct perceiving, as Robert Shaw intuited some years ago (Shaw & McIntyre, 1974). Let me, accordingly, spell out the symmetry in full in accordance with Shaw's original insight that it comprises dual adjunctive relations:

\[(y \circ Y_p) = [(y > i) \cdot (i > y_p)] \cdot [(y_p > i) \cdot (i > y)]\].

The far right pair of adjunctive relations might be called direct selection or direct intention: Since the (intentional) state of the perceptual system \(y_p\) is what it is, then the information \(i\) contained in the structured energy distribution is what it is; since the information \(i\) is what it is, then the property of the environment \(y\) is specified. The relation \(y_p > i\) can be interpreted in four ways that order in degree of difficulty. First, it can be interpreted as identifying limitations of the biological make-up of a given perceptual system that prohibit certain macroscopic properties of structured energy distributions functioning informationally for the given animal. Second, it can be interpreted as the enhancement of some macroscopic properties of energy distributions and the apparent suppression of others—what is commonly termed selective attention. Third, it can be interpreted as the capability of perceptual systems to impose partitionings or structurings on energy distributions that go beyond those imposed by the environment and movement (examples are given below). Fourth, it can be interpreted as the specification by intentional states of the requisite information: To be in the intentional state \(y_p\) is to select/detect \(i\), the property of the structured energy distribution that specifies \(y_p\). I wish to underline that the fourth interpretation refers to a relation that is not mediated by intellectual processes but is direct, in the sense of "due to a symmetry." (Again, I am turning to direct perceiving as the touchstone for formulating and evaluating the relevant conceptions; here the conception is of intentional content.) It is the third and fourth interpretations, particularly the fourth, that do the important work. Some examples from the study of the haptic subsystem comprising the hand and its related (muscular, tendonous, and nervous) tissues will help to make the point.

Suppose that one is asked to wield a visually occluded rod in order to determine where its tip could reach. Experiments show that the distances reachable with hand-held uniformly dense rods are perceived to a high degree of accuracy (Solomon & Turvey, in press). The typical result is that perceived reachable distance relates linearly to actual reachable distance, with a near zero intercept and a slope that does not differ significantly from unity. This linear relation holds for rods of different densities, for rods wielded in, and perpendicular to, the body's sagittal plane, and for rods wielded at different rates. Manipulating the position of an attached weight on an otherwise uniformly dense rod and manipulating where the rod is grasped, reveals that the moment of inertia of the rod about its axes of rotation is the kinetic basis for this haptic distance perception (Solomon & Turvey, in press).

Because the motions of a rod during wielding about axes in the wrist are the three-dimensional motions of a rigid body about a fixed center of rotation, the moment of inertia in the rod's motion equations is in the form of the inertia tensor. The six off-diagonal terms in this symmetric tensor are the products of inertia that engender reactive forces at the center of rotation, causing it to wobble. The three diagonal terms are the moments of inertia with respect to the three coordinate axes. There is an operation—namely, the transformation to the principal or symmetry axes of the rigid body—that eliminates the products of inertia and leaves only the principal moments of inertia on the diagonal (Kibble, 1985). The experimental data have suggested to Yosef Solomon that, under the intention to perceive the distance...
reachable with a hand-held object, the haptic subsystem separates off the principal moments of inertia from the products of inertia. That is, the haptic subsystem behaves in a manner that is functionally equivalent to the principal axis transformation. Moreover, given that the rigid-body motions of a hand-held rod bring about deformable body motions in the tissues comprising the haptic subsystem, the implied functional diagonalization must include the deformation (stress/strain) tensor that characterizes deformable body motions. In terms of the symmetry statement above, the intention \( y_p \) to perceive the distance reachable \( y_r \) with an unseen hand-held rod is realized by detecting a property of tissue deformation \( i \) causally determined by the rod's principal moment(s) of inertia.

A particularly pertinent experimental result is that subjects can perceive fractional lengths when rods are held at positions intermediate between their ends ("how far could you reach with the portion of the rod extending beyond your grasp?"). As before, this perceptual achievement depends on detecting principal moments of inertia—but now they are the principal moments of the rod fraction (Solomon & Turvey, in press; Solomon, Turvey, & Burton, submitted). Apparently, the haptic subsystem can decompose the inertia tensor for a given axis of wielding into distinct components corresponding to the mass distributions above and below the given axis. For simplicity, let \( I \) be the moment of inertia of the entire rod about a given axis and let \( I_a \) and \( I_b \) be the moments of inertia of the rod above the axis and the rod below the axis, respectively. Then it can be argued that when the task is to perceive the whole length of a rod (regardless of hand position), the haptic subsystem behaves as a mechanism that registers the dynamics of the whole hand-held object through the principle of superposition or parallel composition \( (I = I_a + I_b) \). In contrast, when the task is to perceive fractional length, the haptic subsystem behaves as another kind of mechanism, one that filters the dynamic of the requisite portion of the rod through subtraction \( (I - I_b = I_a) \).

As noted, the off diagonal terms of the inertia tensor are associated with bearing forces acting back on the axis of rotation. Basically, they cause it to "wobble." These variable components of the three-space motion of a wielded object are nullified when the rod's motions are about a symmetry axis of the object. Consequently, a person wielding an unseen hand-held L-shaped rod should be able to identify the direction in which the rod is pointing if he or she can register the orientation at which the forces on the axis of rotation in the wrist are at balance. Recent experiments show that direction is perceived haptically (Solomon, Turvey, Burton, & Runeson, in preparation).

The foregoing experimental results and theoretical analyses suggest that, depending on the person's intention, the haptic subsystem behaved as one or another "smart perceptual instrument" (Runeson, 1977; Solomon & Turvey, in press). As I view it, a smart perceptual instrument is a determinate dynamical machine (assembled over the various tissues of the body) that executes a single-valued function. Given the task of perceiving property \( y_x \), it detects property \( i \), a property that maps uniquely to property \( y_x \) and is a special law-based feature of the situation. In the haptic experiments just described, the law-based property is the inertia tensor. Importantly, in those experiments the subjects were unpracticed. The subjects were merely instructed as to the property \( y_x \) that was to be discerned by wielding. For me, the question raised by each wielding experiment is this: How are we to understand the fact that the naive experimental subject "knew automatically" (as it were) which property \( i \) to detect in order to satisfy the requirements of the experiment, namely, perceiving \( y_x \)? What the experiments raise rather dramatically is a why question that is wide in scope: Why do the properties in question go together the way they do? Unfortunately—but, I think, unavoidably—the answer is quite abstract, as
anticipated above. It is that the linkages among the propertied (intentional) states of a perceptual system, the propertied (informational) states of a structured energy distribution, and the propertied states of environmental objects, are fixed by a symmetry principle, namely, that expressed in approximate terms by \( (y_s > y_p) \cdot [(y_p > i) \cdot (i > y_i)] \). Efforts to answer the foregoing why question strictly in terms of evolutionary, developmental, or learning processes will, I fear, fall far short of the mark.

Concluding Remark

If the aforementioned linkages are to underwrite intentional actions generally, that is, apply to each and every animal and hold for all perceptual systems, then they must be invariant over changes in animal design, animal size, animal location, and so on. The symmetry in question, therefore, must be a local (guage) symmetry—the name given to a symmetry that involves transformations that vary from point to point in the domain to which the symmetry applies. I will conclude, therefore, with the opinion that coming to terms with Robert Shaw’s conception of an ecological guage symmetry responsible for direct perceiving will be the key to a thoroughgoing account of animal actions within the program of physics.

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REFERENCES


Solomon, Y., Turvey, M. T., Burton, G., & Runeson, S. (in preparation). Haptically perceiving the direction in which a hand-held object is pointing.


**FOOTNOTES**


† Also Center for the Ecological Study of Perception and Action, University of Connecticut.