ECOLOGICAL FOUNDATIONS OF COGNITION:

II. DEGREES OF FREEDOM AND CONSERVED QUANTITIES IN ANIMAL-ENVIRONMENT SYSTEMS[1]

ROBERT E. SHAW AND M. T. TURVEY

CENTER FOR THE ECOLOGICAL STUDY OF PERCEPTION AND ACTION
UNIVERSITY OF CONNECTICUT, STORRS, CT., USA

ABSTRACT

Cognition means different things to different psychologists depending on the position held on the mind-matter problem. Ecological psychologists reject the implied mind-matter dualism as an ill-posed theoretic problem because the assumed mind-matter incommensurability precludes a solution to the degrees of freedom problem. This fundamental problem was posed by both Nicolai Bernstein and James J. Gibson independently. It replaces mind-matter dualism with animal-environment duality (isomorphism)— a better posed scientific problem because commensurability is assured. Furthermore, when properly posed this way, a conservation law is suggested that encompasses a psychology of transactional systems, a biology of self-actional systems, and a physics of interactional systems. For such a solution, a theory of cognition for goal-directed behavior (e.g., choosing goals, authoring intentions, using information, and controlling actions) is needed. A sketch is supplied for how such a theory might be pursued in the spirit of the new physics of evolving complex systems.

1. How Might Other Disciplines Inform the Theory of Cognition?

The investigation of cognition has flirted seriously with a variety of physical and mathematical tools in an attempt to become a mature science in the spirit of physics, while hopefully avoiding simplistic reductionism. The problems are difficult and to a great extent interdisciplinary. Here is a summary declaration of what we students of cognition typically seek from collateral fields:

From philosophy we seek certain guidelines that might make incorrigible problems more corrigible, render incommensurate kinds more commensurate, or, more often, help transform mysteries into puzzles, hopefully, putting them on the road to becoming scientific problems. Failing this, we might at least learn how to ignore them. From physics we hope to find analogues to psychological phenomena so the unlawful might be rendered lawful. From mathematics we seek ways to make ill-posed problems well-posed, to find connections among variables that appear unrelated, and a variety of generally consistent schemes of description from which we might select one appropriate to our problem.

Hence philosophy may help us frame our problems, physics may predispose us to certain forms of principled explanations, and mathematics may provide us with schemes for expressing the principles and problems that, when judiciously used and empirically interpreted, lend consistency and validity to our efforts.

As a field, cognition faces an additional problem. Where sufficient agreement exists in experimental design and statistical methods to have similar standards and criteria for peer review across its best journals and major funding agencies, purely theoretic efforts are less likely to be understood or appreciated. No consensus exists concerning which problems are most fundamental or which theoretic principles are most useful.

Because there are no clearly defensible laws, the job of students of cognition is made more difficult.

In the present article we identify and explore the *generalized degrees-of-freedom problem*. This problem is a major bulwark to a successful theory of how animals can know about their environments and behave adaptively with respect to them. Moreover, it is a problem that seems sufficiently fundamental and general to warrant concern by all scientists. In preview, a solution to this problem seems to entail the discovery of a new conservation law, one defined at the level of animal-environment systems.

2. The Generalized Problem of Degrees of Freedom

Bernstein (1935/1967) was the first to draw attention to the fundamental importance of this problem for explaining the control of behavior. He posed the following difficult but incisive question "How can a neuromuscular system with an exorbitant number of degrees of freedom be made to act as if it had but one degree of freedom?" (see Turvey, 1990). Gibson (1966, 1979) promoted a related idea. He argued that, in contrast to its use in communication theory, *information* should be construed as specificity of the useful rather than as the uncertainty of the specific. The latter sense of information was, for Gibson, the best way to understand how perception could control behavior (see Turvey & Shaw, present volume). Perception controls behavior by detecting informational constraints specific to goal-paths (Gibson, 1979; Shaw & Kinsella-Shaw, 1988). Goal constraints, as compared to physical constraints, can be considered extraordinary (Kugler & Turvey, 1987; Turvey, 1986), for they take the form of a rule that prescribes how one should act if some outcome is intended. More to the point, the prescriptive rule asserts that one should act so as to change the current information, which is less specific to an intended outcome, into information that is more specific. With these intentional rules for action, Gibson opened wide the door to an ecological approach to cognition.

Such “rules” he assures us, however, are not computational; they are more in the nature of laws at the ecological scale. When presented in dimensionless form, they may apply across species. Their effects may be observed whether or not an animal or human is aware of them. Perhaps, they conform to Wittgenstein’s notion of a rule entailed by the behavior and its context rather than to a rule procedurally involved, like a recipe, of which the agent must be aware.

It is worth noting that this “rule” is more like a law, but a law of quantum physics rather than classical physics. Quantum laws apply at the subtle scale of weak potentials (usually but not necessarily identified with smallness); they relate expectations across measurement situations, and in this sense are informationally based. They are prima facie about what we can know, not about what is (except under certain realist philosophical assumptions). Classical laws relate facts about energy, forces, etc. across physical situations. Hence a Gibson rule for the perceptual control of action is a law in the quantum sense, but not in the classical sense. Because this is so, we might tend to find help in characterizing them from a study of the mathematics used in quantum physics. Keeping this in mind will help in understanding the main points that follow.

The answer to Bernstein’s question, couched in terms of a Gibson rule, is that a system with many degrees of freedom can act as if it were a simpler system only if sufficient constraints, or linkages, are established among its components by coupling them into a synergy. What are the possible sources of freedom (the removing of constraints) and constraint (the curtailing of degrees of freedom)? Three sources might be identified: external force fields of physical origin, internal force fields of biological origin, and information fields of psychological origin—in the ecological sense.

The coupling of external, environment-based force fields with internal, organism-based force fields by means of forceless information fields (Kugler & Turvey, 1987, 1988; Kugler, Turvey, Carello & Shaw, 1985) poses as yet unsolved problems for cognitive theory. It is possible, however, to identify some of the most important characteristics that these solutions should have. The starting point is information's nature. How can it couple two systems, such as an animal to its environment?

3. Systems Informed by Interaction, Self-action, and Transaction

In physics the freezing out of degrees of freedom is achieved automatically by laws that entail Hamilton's least action principle (where action is mass x distance x speed). Such physical degrees of freedom are a function of whether the particle is located in a field-less region of space (free fall), or whether in a region of space dominated by a field of external forces (e.g., gravitational or mechanical). Following Rosen (1978) we might say that a system moved from a force-free region of space-time to a force dominated one becomes dynamically informed (literally, "takes on form"). Under this view, information is simply that which imparts "form" where the latter is simply just another word for "constraint." Where "free-form" means an unconstrained, or random, shaping of material, so "free-fall" means an unconstrained shaping of its trajectory, a random path. Information in the preceding sense can be called *dynamical.*

To obtain the sense of information that will do most work for a theory of how animals know about their environments, we need to add "specificity" to the connotation of the term (Gibson, 1966, 1979; see Turvey & Shaw, present volume). Information in the specificational sense picks out a few things from a background of many things. It is selective or choice-like. Preserving both connotations, we then have a concept of total information that is the sum of two complementary functions: the dynamically informing and the intentionally specifying—where being *intentional* is to be *about something*, to refer beyond itself, in the philosophical sense.

It is, we think, an egregious and dangerous error for a theory of cognition to take either meaning alone, say, to take selectivity alone, as done by Shannon (Shannon & Weaver, 1949), for this leaves information perspective-free, unscaled, and unconstrained by dynamical law. Better to keep information bound to physical parameters (e.g., Boltzman's constant in its negentropic interpretation), and start from there to determine its additional uses in biology and psychology (Kugler & Turvey, 1987; Shaw, 1985). Right or wrong, this is our attitude and plays a major role in how ecological psychologists do their work as scientists,

It is important to admit right off that informable systems are the general case. Systems in free-form or free-fall are the exception since they only exist temporally and locally, and, strictly speaking, only at limit—in the mathematical sense. Informable systems may be of two kinds: being externally informed or self-informed. Ordinary physical systems are externally informed systems. These are the special case since they do not have all the properties of living systems, while living systems have all the properties of physical systems plus additional ones. Perhaps, the chief difference between physics and the life sciences is that the former studies simple systems relative to the complex systems studied by psychology and biology. This claim was heresy among nineteenth century physicists but today is a growing consensus among the "new" physicists, among whom we must number ecological physicists. Let us consider these differences.

Traditionally defined physical systems are solely *interactional;* when acted upon by a force, an immediate reactive force tempers their response (in accordance with Newton's law of action and reaction). However, there are some systems that are *self-informable*, in the sense of being self-motivating and selfcontrolling. All life-forms fall into this class, at least as far as we know. In addition to being interactional, as all systems with mass must be, these are also *self-actional*; they are capable of a delayed reaction in addition to the immediate reaction which they may modulate by the addition of self-generated counter-forces. To do so, however, they must have complex interiors, an on-board (metabolic) potential capable of biogenic forces that may be used to cancel, modulate, or delay their immediate reaction to an external force (Kugler & Turvey, 1987). Biogenic force modulation requires scaling information if the potentially deleterious effect of an external force is to be controlled. Such systems are informable by evolutionary or self-styled edicts as a function of, or sometimes independent of, local environmental force fields.

Systems that are more dependent on information fields, with information defined in the specificational sense, may be driven by intentions that are specific to a nonlocal, essentially forceless field—a goal. The field of goal-specific information is force-free when, at the scale of the system's mass, no significant momentum transfer takes place from the external field (Kugler & Turvey, 1987; Kugler et al., 1985; Turvey 7 Shaw, 1995). When so, this leaves the system's internal force field in sole charge of its control while the environmental information field makes goal-specific demands on that control. Systems that conduct their business with the environment through information will be said to be *transactional* rather than simply self-actional (Dewey & Bentley, 1949; Shaw & Turvey, 1981; Turvey & Shaw, present volume).

Transactional systems do not merely modulate their reactive forces haphazardly, or, at least, natural selection weeds out those that do. Fit transactional systems are adaptive because they are not merely informed but are specificationally informed about life-sustaining resources whose procurement is possible and intended. Across all species this is true. It is not (yet) true of artifacts (e.g., computers or robots). Why this difference? We think it exists because the natural species share a secret design feature that the artificial species do not. Organisms deal with their environments in a lawful manner that has not yet been built into machines. We will suggest that they conserve *total generalized action*.

Being information-driven does not preclude a transactional system from being force-driven. Transactions subsume self-actions and interactions. Biology makes possible extra degrees of freedom that may be, but need not be, used to modulate external forces by internal forces. Ecological psychology, among other things, is the study of how these extra degrees of freedom may be used to orchestrate intentional acts.

4. The Plenitude Hypothesis and the Sculpting Metaphor

The most straightforward strategy for solving the degrees of freedom problem is to search for sources of constraint. The sources of constraint must be one less than the degrees of freedom. Why one less? A degree of freedom must exist if the system is to follow the path that the laws of nature dictate. In nature, there truly are no dynamically stultified systems, they are all in process and continue to change over time. The apparent persistence of certain phenomena, like the oceans and the mountains—even the moon orbiting the earth, or the sun rising and setting, is not permanent but only temporary.

Indeed, the dean of contemporary cosmologists, John Archibald Wheeler, asserts that the only fundamental law is mutability itself—a law without laws (Wheeler, 1982). No laws existed prior to the "big bang." Rather the laws developed as the universe evolved. No laws of chemistry until particles coalesced into molecules, no laws of geology until the earth formed, no laws of biology until there was life, and so forth. Laws express what is structurally stable in nature so predictions are possible. Under the law of universal mutability, structures are but slow functions; hence laws must evolve. In the beginning, there was only a singular compacted action (a dimensionless form of Planck's constant)—energy to be distributed over time—so everything must come from it (unless there are also local sources of continual renewal, see below). The initial condition was a singular action integral to be differentiated over emergent space-time into energy, forces, momenta, and velocities.

On earth, the environment is also characterized by change rather than absolute persistence, or as Gibson (1979) put it, persistence amidst change and persistence of change. We live in a plenum of possibility where all perception is event perception, the perception of changing things (Turvey, 1992), and is so whether events transpire slowly or swiftly (Shaw & Pittenger, 1978; Shaw, Flascher, & Mace, 1996; Warren & Shaw, 1985). This event perception thesis follows directly from the new physics emerging at the end of the millennium. The fundamental reality consists of events and not of things. Recent theories of the cerebellum suggest a useful metaphor. The cerebellum is that part of the brain most centrally involved in the dynamical control of movement, and seems to be continually firing (Braitenberg et al, 1997). Timing signals arise from systematic suppression of unwanted firings. They are, so to speak, “sculpted out of this background of excitation” as miniature tidal waves that flow as coherent paths of excitation (Shaw, Kadar, & Turvey, 1997; Kadar, Shaw, & Turvey, 1997). This metaphor of “sculpting from a background of excitation” captures the fundamental mechanism of the new physics.

This image of reality arising out of a background of raw dynamical potentiality, by processes that carve relative persistence from chaotic excitation, also fits the quantum theorists’ notions about the creation-annihilation dynamics of the (false) vacuum. Under this modern view the vacuum is not an empty, inert void but a cauldron of subtle energy from which particles emerge and into which they disappear (Finkelstein, 1996). Postulating the vacuum as the engine of continual renewal, endorses a truly Heraclitean view of nature. To avoid *creatio ex nihilo*—creating the world from nothing—the vacuum is no longer a dead-end void but a creative conduit to a plenum (a Greek word meaning “bountiful” but used philosophically to denote a cornucopia of pure potentiality).

The plenitude hypothesis asserts that nature is a plenum, or superabundance, of real possibilities—a view consistent with ecological psychology (Turvey, 1992; Turvey & Shaw, 1995). The historical development of the plenitude hypothesis was traced earlier this century by Lovejoy (1936) in his widely acclaimed and prophetic book, *The Great Chain of Being*. This idea is of a plenum that sits behind observed reality is also fundamental to modern physics, and sums up its weakened view of determinism: If laws of nature do not disallow something, then it exists.

Modern physics is not about finding the causes that make something’s existence lawfully necessary. It is about exclusion or censorship of those things not allowed. As in the case of change, no positive cause for is required or even possible. All entities or processes are suspected to exist until cleared of the charge. All phenomena, no matter how weird, have equal ontological status. For one thing to exist rather than another, it needs to be most compatible with the other potential existents. It then moves across the ontological threshold to become actualized.

This is analogous to an argument by Leibnitz, one rooted in his notion of compossibility, or mutual compatibility. He held this argument in abeyance as a possible replacement for the more simplistic, but more Church approved, postulate of pre-established harmony. His follower Herbart (1824) framed a theory of consciousness from this notion of compossibles residing in a psychical plenum. Ideas remain below the threshold of consciousness until they reach a critical apperceptive mass, then they come into awareness. The most buoyant ideas are those that are most compatible with the most other ideas. If we forget the mental aspects, and focus only on the mutual compatibility argument, then we have the equivalent of the dynamical phase correlations that underlie the sculpting mechanism used in the new physics (Feynman & Hibbs, 1965)..

Similar arguments have been applied in neuroscience by quantum brain dynamicists (Jibu & Yasue, 1995). They argue that coherent brain processes, called Bose condensates, arise from a creation-annihilation dynamic between photons, electrons, and water molecules in the brain. Such arguments reflect a deep belief in the plenitude hypothesis and the sculpting mechanism. A cerebral mechanism sculpts from a background of excitation—a plenum of possible excitonic waves—whatever cerebral events are needed to underwrite thoughts, feelings, memories, perceptions, or other experiences. In this way they hope to offer a credible scientific account that resolves Chalmer's easy problem.

5. Chalmers' Problems

Chalmers (1996) has identified two problems faced by neurocognitive science if either of these strategies were adopted—the "easy" problem that presumes a necessary alignment between experiences and events in a physical (e.g., neurological) substratum and the "hard" problem that we will define in a moment. The so-called "easy" problem (which of course may be extremely difficult scientifically) is faced by the theory of mind which seeks to determine what events in the physical substratum (the brain?) take place concomitantly with the associated phenomenological events (experiences).

The Fechner-Spinoza principle of psychophysical correspondence is an example of an attempt to solve to the "easy" problem by postulating the solution: For every physical event there is a concomitant mental event, and for every mental event there is a concomitant physical event (Bain, 1873). What is the evidence for such a strong claim? There is none, since the induction is hardly fulfillable but, more fairly, none is intended. It is rather a strategy, a kind of license for a neuropsychology fishing expedition. In any case, such views leave aside the issue of how experience arises, where its content comes from, and only addresses those aspects of the physiological processes to which an experience corresponds.

By contrast, the "hard" problem requires more than mere concomitance but must explain how the character of experience (content) necessarily derives from, rather than merely corresponds to, the character of physiological events. It must address the sufficiency problem as well: how can the psychological content of experience be restricted to the variables describing the physical content. Consequently, it is difficult to see how a prima facie case can be made that either of these strategies gives us a theoretical handle on how to address the "hard" problem scientifically. The problem remains a mystery—a puzzle with an ontological enigma at its core.

6. Peirce's Chance Discovery of Order in Entropy

From the discussions above, the metaphor of "sculpting from a background of excitation" may be too exemplary of nature to be treated as mere metaphor. Perhaps, it models the mechanism of the millennium, having power to heal the schisms that separate psychologists from other scientists and from each other. What might be its physical origins?

The brilliant friend of William James and co-founder of American pragmatism, Charles Sanders Peirce, presented an elegant argument for why physical reality might naturally contain a scuplting mechanism (Peirce, 1892). After describing the inevitable heat death of the universe as entropy accrues according to the second law of thermodynamics, Peirce observes: being part of the entropy producing process, no force left to its own designs can counteract the lawful degradation of order. However opposing this lawful disordering process is "chance"—the opposite of law. Chance offers an extra degree of freedom to physics by which life-forms can emerge.

Chance, by opposing the second law, allows a kind Prigoginean order (Prigogine, 1980, 1997) to be brought into the world in spite of its entropic tendency. Put into current idiom: Chance is just a looseness in the determinism of physical laws which, by the plenitude hypothesis, gets automatically filled up with excitation from the vacuum—a kind of space-time foam (Wheeler, 1982).

The sculpting of intentional paths from this background of excitation cannot come from opposing, head-on, the laws of nature as conceived by 19th century science. The dissipation of energy by the regular laws of nature allows, by their inherent laxity, a home for another process, a counter-process whose tendency is a filling in of the entropic seams with order. This counter-process is not really chance, or randomness, but merely seems so from the perspective of the ordinary laws. From their perspective, the counter-process appears both nonholonomic and nonlinear, as the ordinary laws do from its perspective.

The aforementioned dual, dynamical, antisymmetric processes are equally real and equally physical; but being contrary in direction, they just are not physical in the same sense. Nature no more favors one than the other. Neither holds hegemony over the other. There must be a point however, as Peirce assures us, at which the two tendencies achieve balance. The catabolic Second Law and its anabolic Prigoginean dual may hunt for a metabolic equilibrium without reaching ultrastability (Swenson & Turvey, 1991). Their balance will be at best approximate, and therefore tolerant of life for as long as this balance holds.

The master equation for describing this hunting for balance is not a genetic algorithm with an a priori, God-given harmony to achieve, but more like a dynamical ecosystem equation of the Lotke-Volterra variety (such as might be formulated for species competing over limited resources). Balance must be earned and sustained by continual work. This dynamical balance law foreshadows the existence a deeper conservation than energy or momentum conservation, one that subsumes the other conservations. This new, putatively conserved quantity, is the generalized total action referred to above. It is defined as the time integral of energy used to inform and control a relatively closed system so that it behaves in a manner that satisfies certain boundary conditions (one of which, for certain systems, might be a goal). Application of this universal "sculpting mechanism" to ecosystems naturally follows (e.g., Shaw & Kinsella-Shaw, 1988; Shaw, Kadar, Sim, & Repperger, 1992).

These counter processes are dual in the sense of being mutual and reciprocal (Turvey & Shaw, 1995; see Turvey & Shaw, present volume), that is, where one is free the other is constrained. We might say, one is the environment of constraint to the other's freedom as process—a kind of cosmic ecosystem. The physics appropriate to studying this fundamental engine for life must be defined at this proto-ecological scale. Such an ecological physics must countenance both processes, and aims at laws that allow one process to be harnessed by the other. Its task is to explain how their loose coupling, or *graded determinism*, supports life and the informing of the controlling forces that sustain it.

7. Ontological Descent from Possibility to Actuality

In an attempt to catalogue the extra-degrees of freedom that accrue from these dual processes, and for which ecological physics is ultimately accountable, we offer the following bookkeeping scheme.

-------------more constrained------------------>

possible worlds > potential worlds > actual worlds

<-------------more freedom--------------------

Actual worlds obey a cascade of constraints from the left to the right. The cascading constraints imposed squeeze out the available degrees of freedom. Existence occurs when sufficient constraints confine variables to single values, and they become constants, or the "value of a bound variable" (as Quine suggests). Variables are bound to the degree they satisfy the contexts under which they are nested. Hence for a system to exist in an observed state, it must have "constraint satisfaction;" its degrees of freedom problem must be implicitly solved, otherwise its behavior would be indeterminate—an impossibility in nature. The constraints to be satisfied are denoted below.

generalized action conservation > other conservations > boundary conditions >

dynamical laws > perspectives > scales > action rules > values

Considerable discussion is needed to clarify this ontological descent scheme. We can venture here only a brief sketch of its levels.

At the possible worlds level, the only constraint is a weakened version of the classical logic law of noncontradiction. Under the strict determinism of the old physics, this law had to take the form of an exclusive disjunctive proposition (not both p and not-p), where nothing can be both true (existent) and false (nonexistent) under exactly the same circumstances. By contrast, under the current graded determinism of the new physics, with its endorsement of the plenitude hypothesis, the law of noncontradiction is weakened. It now becomes an inclusive disjunctive proposition (either p or not-p or both p and not-p). Consequently, states are sometimes indefinite superpositions of all possibilities that laws allow.

Moreover, increased freedom allows for the dual dynamical processes discussed earlier and gives legitimacy to quantum physics' view of reality as a plenum of possibilities. Specifically, it allows for the superposition of quantum states, as exemplified in the famous Schrödinger cat problem. By Heisenberg's uncertainty principle, if a cat can be potentially killed by a random quantum event, the outcome remains in limbo, with the cat being neither living nor dead, or both, if you prefer, until observed or measured. Observing the situation is an occasion on which the wave function of the cat-and-apparatus collapses into one of the two possible, superposed states. Observation is supposed to cascade sufficient constraints to make the cat's indefinite possible state (both alive and dead), into a potential state (either alive or dead), to being a unique value of a bound variable—a constant (say, alive).

Does observation really cause the collapse of the indefinite into the definite, implying Cartesian interaction between mind and matter? Wigner (1970) has suggested it does because consciousness plays the role of a state reduction operator. Or, does it simply occasion it, implying Leibnizean parallelism? The jury is still out on this issue (See Penrose, 1996). As ecological realists, we consider the question to be ill-posed. We agree that it is a degrees of freedom problem and, perhaps, the most fundamental example. But we disagree that mind-matter dualism is a useful way to approach its solution. The ecological approach would substitute the animal-environment duality in the place of the mind-matter dualism (Michaels & Carello, 1981; Shaw & Turvey, 1982; Turvey & Shaw, 1995; Turvey, Shaw, Reed & Mace, 1981; see Turvey & Shaw, present volume). How might this orthogonal strategy work in this case?

The issue is not whether we observe the cat and find it either living or dead, but whether the cat observes us as well. If it does, then neither it nor we can be dead, indefinite, or nonexistent, in the usual meaning of these words. If the observer and the cat can have mutual and reciprocal perspectives, then they are dual observers, a social dyad, sharing an environment (laboratory). Hence an ecosystem exists. Two beings that share the same environment must logically be recipients of the same cascade of constraints. As partners, they make the ontological descent together, coupled by information, satisfying the same conservations, governed by the same laws, under reciprocal perspectives, at a mutual scale, until each becomes the value of the other's bound variable.

Hence at the macroscale where such mutual information exists, all the variables of the situation are mutually constrained. Their wave functions are perfectly in phase. When this happens, harmony is achieved *a posteriori*. It is established dynamically. There need be no assumption of its *a priori* pre-establishment. In physics this is known as solving an eigenvalue problem. The best formulation of this actualizing process, in our estimation, takes the form of a Feynman path integral. In ecological terms, it represents how a process, termed an *effectivity*, squeezes out the degrees of freedom from an *affordance*, to yield a specific, actual action (Shaw, Kadar, & Kinsella-Shaw, 1995; Shaw et al., 1997; Kadar et al., 1997). It works this way.

8. Feynman Path Integrals and the Generalized Action Principle

Let's not argue about whether the ontological descent scheme is true, or even if it could be true. Not being philosophers, we are only interested if it might be a useful idea. Does it have any legitimate scientific interpretation? More exactly, does it suggest a way that a particle (or an actor) might get from one point to another in the environment, say, by following a Gibson-like action rule that solves its degrees of freedom problem.

In the old physics, Hamilton's principle of least action somehow picks out the path actually followed from all possible, less stationary (under variation) paths. It is not at all clear how it does so, that is, how the particle is constrained to a unique path. Poincare' (1905/1952) said the claim that Hamilton's principle provided an explanation was an offense to reason. He argued that finding the least action path implied that the particle first had to try out all the other paths to see which was least effortful. How could it do so? Does it explore all the paths “off-line” from ordinary reality, while time is mysteriously suspended? Such an exploratory activity could not be dynamical since this would violate the conservation principles. The fact that we do see paths of objects does not help since perception is imprecise, being limited to a grain coarser than that of quantum uncertainty. As discussed earlier, conventional formulations of quantum mechanics provide no help since they have no state reduction operator. Is the path concept therefore useless?

Many physicists resigned themselves to the indefiniteness of paths, while others continued to believe that definite classical paths really do exist even if Hamilton’s principle does not explain how. An impasse was reached and Poincare’s objection continued to stand unchallenged for a half century or more, mostly because it was ignored (Yougrau & Mandelstam, 1979). In this context of extreme pessimism and the misplaced optimism regarding the reality of paths, Feynman’s eventual insight was quite unexpected.

Working from a suggestion by Dirac, Feynman ignored the pessimism and took a positive attitude toward this problem. He reasoned that if a unique path is not possible, then all possible paths are allowed, a clear application of the plenitude hypothesis. Furthermore, he showed how the classical path could be recaptured: If each path could be weighted at each step by an action factor, then so can each space-time point the path crosses. Next, remove the paths from consideration, what is left is a space-time array of point-action weights.

Finally, let each of these action values be represented by a vector perpendicular to each point. In this way, they describe an action topography with peaks and valleys. The minimum path is then found by the particle making the steepest descent through the hills and dales. This descent avoids being trapped in local minima because a nonlocal correlation is introduced (analogous to "cooling" in simulated annealing techniques). The amplitude of these action peaks are cross-correlated by a field process in the manner of Huygens' principle of constructive and destructive wave interference.

Under this principle those paths that are most highly correlated are those that are most stable, least busy, and these are exactly those with minimal values. Feynman proved this with his path integral approach. His approach provides a different take on physics, and, although difficult to solve in closed form if more than two degrees of freedom are involved, but can be readily simulated "on-line" by Monte Carlo techniques (Landau & Mejia, 1997). The Feynman path integral provides one way to represent mathematically an effectivity, or sculpting mechanism. It carves out an actual tolerance region around the classical path. The former is psychologically more realistic than the latter because perception (measurement) has finite resolution.

In sum, Feynman showed that each path is more or less in dynamical phase with the other possible paths. Thus they each contribute to the sum of amplitudes which is greatest in the vicinity where the classical path is to be found by standard variational techniques. The path integral approach essentially gives a "global" formulation to classical field theory and, for our purposes, to intentional dynamics.

Feynman's elegant generalization of Huygens' action principle achieves an explanation for the appearance of tolerance corridors around the minimum path. Application of Hamilton's action principle requires that paths have stationary end-points, that there be no background of excitation. By contrast, Feynman's action principle uses this nonstationarity to allow phase-correlated paths to emerge from that noisy background. In this way the excitation acts as a sculpting tool *sui generis* for carving out the most tolerant path.

The final trick is to make each level in the ontological descent a sum of Feynman path integrals. With such a fundamental principle available, perhaps, the science of cognition and the other sciences can work from the same page in nature's book on mathematical strategies.

9. The Usefulness of an Action Conservation Measure

We conclude by summarizing some of the chief reasons that having a conservation is important to a developing theory of cognition. A conservation is a quantity whose number before and after a manipulation, experimental or natural, remains invariant. It is a unity that may be partitioned such that when the partitions are recombined, the unity is restored without loss or gain. Conserved quantities may redistribute themselves so that a loss in one place is always complemented by a gain in another place. In this way, a conservation provides a useful measure, indeed the best measure, for a dynamical systems where most everything else is changing. It represents a persistence in the midst of change, an invariant. Information specific to a conserved quantity will likewise be conserved (e.g., in phase space, consider the conservation of area of a limit cycle in spite of shape changes; it is information specifying the conservation of momentum over space.)

With an invariant information measure, you can quantize the aspects of a task yielding path solution data. With these path action numbers one can then compare and order paths accordingly to

(1) compare novice paths to that of experts;

(2) compare the levels of task difficulty under different experimental conditions;

(3) measure improvement in task performance over trials

(4) classify task control strategies in terms of efficient use of space, time, energy, or momentum changes .

Although students of cognition have measures of each of these, the measures are typically post hoc rather than principled, and are not guaranteed to be measuring the same thing. Having a conserved quantity on which to base the above measures would avoid these problems and help the study of cognition to move to a higher scientific plateau.

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