[1]Intentional Quantum Dynamics: Entangling Choices and Goals

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Abstract

An unresolved problem in psychology is prospective control, i. e., the question of how information about what is intended *to be done* can influence what is *being done* (Turvey, 1992). Over the past quarter century we have addressed this issue by working toward an intentional dynamics approach based on the Feynman path integral. From initial to final condition, i. e., from goal-selection to goal-satisfaction, the kernel of the integral's transform, $K(t_1,t_0)$, somehow propagates a path that solves a two-point boundary problem—just as any constrained particle must. Here we treat choices at choice-points (including the initial, current, and final states) encountered along goal-paths as superpositions. Intention, or goal selection, is hypothesized to be just another word for entanglement whose path stability can be measured using quantum correlation. Also, we hypothesize that objects' multiple uses (affordances) encountered *along the way* can be treated as superpositions that "collapse" as the goal-paths are successfully propagated. Under this approach, we hypothesize that intentional activities are made possible by the system's entanglement dynamics—the progressive making and breaking of entanglements in order to stay on a goal-path.

1 Introductory Remark

The question that motivated this conference and the formation of the Mind-Matter Society is whether and to what extent there is an interaction between psychology and quantum mechanics—either theoretically or empirically. The current paper suggests one way in which to characterize such an interaction. It is not unusual for quantum physicists to claim there to be an intrinsic connection between their field and psychology. Here is one one such instance offered by Schwartz, Stapp, and Beauregard (2004): "Quantum theory is built upon the practical concept of intentional actions by agents. Each such action is a preparation that is expected or intended to produce an experiential response or feedback. For example, a scientist might act to place a Geiger counter near a radioactive source and expect to see the counter either'fire' during a certain time-interval or not 'fire' during that interval. The experienced response, 'Yes' or 'No', to the question, 'Does the counter fire during the specified interval?', specifies one bit of information. Quantum theory is thus an information-based theory built upon the preparative actions of information seeking agents" (p. 9).

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Psychology has been developing as a science but without a clear idea of what kind of science it might become. As quantum theory developed it soon became clear that it differed from classical mechanics in very important ways. Rather than being local and deterministic, it proved to be nonlocal and nondeterministic, instead of *either_or* but *not both* logic, because of superposition it has an *either_or* and *both* logic. Similarly, ecological psychology is dramatically different from classical psychology (i. e., behaviorism and cognitivism) in an analogous way. Next, an important way is discussed.

2 Ecological Laws as Analogous to Quantum Laws

Classical mechanical laws apply to predict events: Given the appropriate initial conditions (i. e., the mass and layout of three balls A, B, and C so that if $event_1$ occurs (e.g., ball A strikes ball B), then $event_2$ (i. e., ball B strikes ball C) necessarily (lawfully) follows. Traditionally. Psychological laws have been assumed to take the same causal form: Given the appropriate initial conditions, normal organisms (with proper learning history, attending to stimulus, and so forth), then if $event_1$ occurs (a stimulus event), then $event_2$ (a response event) typically (lawfully) follows. Here, as Skinner (1977) suggests, the stimulus, although not truly a force, acts like a force. and the control law' (next state function), although not truly a law, acts like a law to move the organism into its next state from which it emits the observed behavior. If the state transition is associative, then this form of law fits a *stimulus-response behaviorism*; however, if the state transition involves a representation, or symbol, then this form of law fits *cognitive psychology* (Fodor & Pylyshyn,1988).

This classical law form, however, fits neither quantum phenomena nor ecological psychology phenomena (e, g., intentional dynamics); rather, they both take a different law form. It is generally agreed that quantum mechanical laws do not predict events with absolute certainty, as deterministic classical laws are supposed to do; rather they predict only the probability that subsequent observations (measurements) will follow from previous observations (measurements) if a certain relationship holds between a state function and characteristic properties of the situation (Wigner, 1970). As indicated, ecological psychology requires laws that operate similarly.

Consider a role for the perceptual control of action (Gibson, 1979), say, as formulated from the perspective of a prey engaged in a prey-predator competition. *If you (the prey) intend to escape the predator, whose image is expanding in your optic array, then intend to move so as to make the predator's image contract!* Here, analogous to the quantum law formulation, the law relates a previous observation (information) to a subsequent observation. The quantum mechanical interpretation of intentional dynamics has a similar form.

The Table below compares the different laws discussed. Both forms of the classical law (I and II) relate event to event, while the quantum-type law form (III and IV) relate information to information through a function that is the complex conjugate of the characteristic property of that information. In the quantum case, a state function does so, while in the intentional dynamics case, a path function (an effectivity) does so.

	KIND OF LAW	FORMULATION
I.	Classical mechanics	$event_1 \rightarrow law \rightarrow event_2$
II.	Classical psychology	stimulus → law → response
III.	Quantum mechanics	$observation_1 \rightarrow law \rightarrow observation_2$
IV.	Ecological psychology	$perception_1 \rightarrow law \rightarrow perception_2$

3 Background

Two decades ago, we wrote a paper for a Neurodynamics conference entitled "Modeling systems with intentional dynamics: A lesson from quantum mechanics" (Shaw, Kadar, & Kinsella-Shaw, 1995). There we discussed the putative relevance and significance of Feynman's path integral, FPI (or, 'sums over histories') approach to quantum theory for developing a psychology of goal-directed behavior. A little later, we showed how the FPI might also be relevant to neuroscience by using it to model fundamental cerebellar activities (Shaw, Kadar, & Turvey, 1997, & Kadar, Shaw, & Turvey, 1997). Fifteen years later Ittai Flascher completed an experimental dissertation in our laboratory whose data was modelled quite well by a Markov chain Monte Carlo rendition of a Feynman path integral (Flascher, Shaw, Michaels & Flascher, 2006). And, more recently, we showed how intentional dynamics might be treated under a thermodynamics framework (Shaw & Kinsella-Shaw, 2012).

Today we are continuing that program by providing some reasons to believe goal-directed systems are best understood when treated as quantum systems rather than classical systems. An inventory of the most relevant quantum theory concepts to be adopted includes superposition, interference, entanglement, and quantum correlation.

4 Introduction

Historically, attempts to provide traditional scientific accounts of systems that appear end-directed were stymied by the general ban on teleological reasoning. Such explanations have been deemed unworthy for two reasons: First, they violate mechanistic principles by invoking *time-backward* causation that puts effects before causes and, second, because they depend on, to use Einstein's words, "spooky action-at-a-distance" that violates the consensus view that distal influences cannot produce proximal effects without acting through mediating causal chains. Indeed, the concept of field was originated to be the mechanism for filling this empty gap.

In modern physics these objections no longer hold—and were even ill-founded in classical physics since notable examples of both backward causation and action-at-a-distance existed but were ignored. Hamilton's principle of least action and Maxwell's vector potential are two such cases. We briefly review the history of these shibboleths and the reasons they were over-turned to help set up our thesis that many systems (e.g., least action paths, black holes) do, in fact, exhibit prototypic *intentional dynamics*—the term we use to identify goal-directed systems and to refer to principled aspects of their common dynamics.

To emphasize how ubiquitous goal-directedness is in nature, we begin with a rather odd case.

5 The Intentional Black Hole

Let's allow ourselves to entertain a wild hypothesis. What if intentionality were rooted in the fabric of space–time as a ubiquitous physical phenomenon, then shouldn't it show up in some ways that are independent of living systems. Perhaps, there is 'prototyping' in nature whose expression in living systems is but a derivative outcome of something far more basic. Consider the following curious case of the "intentional" black hole as evidence that intentional connections might be as fundamental in nature as causal connections. (For clarification. see note at end of Section 11)

Most of us have a nodding acquaintance with those denizens of deep space known as "black holes." However let us remind ourselves of some of their key properties. A black hole is a celestial object, probably a massive old star that has collapsed under its own gravitational attraction so that particles trapped inside its boundary, or event horizon, cannot escape with a velocity less than that equal to the speed of light. There is also a boundary outside the black hole such that objects that cross it are captured and dragged into the black hole.

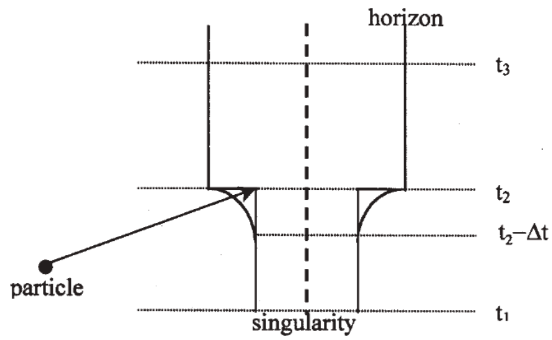


Figure 1. Particle colliding with a black hole.

Figure 1 shows the make-up of a black hole to include a singularity, a point in space of essentially zero dimensions surrounded by a horizon. The temporal trace of the singularity is depicted as a dark vertical line with time running upward (note the order of time tags). The event boundary is depicted as the cross-section of two cylindrical sleeves of different radii, $(t_1 - t_2)$ and $(t_2 - t_3)$. A nonlinear jump in the size of the radius of the cylindrical boundary takes place whenever a particle is swallowed by the black hole at time t_2. Although the radial increment must be a discrete jump to accommodate the particle mass instantaneously added to the black hole, the field properties surrounding the black hole require that the transition from the smaller to the larger radius be smooth and continuous. Hence, there is a conflict here between quantum theory and general relativity: On the one hand, causality requires that the radial change be a retarded potential and not take place until *after* the particle is swallowed (i. e., the effect must follow the cause), whereas, on the other hand, the field property requires an advanced potential so that the smooth transition indicated by the arcs connecting $(t_2 - \Delta t) - t_2$ must take place *before* the arrival of the particle (Thorne, 1994, pp. 417- 418).

In other words, if the horizon is to undergo the smooth continuous change field theory demands, then it must begin expanding before the particle arrives—a clear case of an anticipatory response where the effect precedes the cause! Note especially, that the degree of the expansion must be specific to (i. e., informed by) the mass of the particle and its time of impact. Does the black hole then somehow "know" the intention of the particle? If it were sentient, we would ask three questions: (a) In what form is the information about the impending collision of the particle made available to the black hole? (b) How is that prospective information detected by it? And (c) how is the anticipatory response of the horizon's radius controlled by the prospective information?

This may all sound quite farfetched, but the alternative explanation is no less so. For if there is no prospective information, then it must instead be a case of action-at-a-distance without any way to specify the black hole's control parameters. If so, then how does the distal particle cause the black hole to begin its early responding? To avoid action-at-a-distance and to preserve both the causality condition and the continuity principle that underwrites relativistic field theory, we have no choice but to postulate an information field that is co-extensive with the gravitational field. (It is important to note that this assumption of an information field is a hidden variable theory and inconsistent with Bell's famous theorem, namely, that no physical theory of local hidden variables can ever reproduce all of the predictions of quantum mechanics.)

There is no known energetic field to support the prospective information needed to specify the hole's advanced response to the particle's impending collision; nor is there any known mechanism present in the hole for detecting and using such information to effect that anticipatory response. Hence the mystery.

This black hole example is dramatic but not a standard one. Here is a standard example. It is possible to polarize two particles in a single quantum state such that when one particle is observed to be spin-up, the other one will always be observed to be spin-down, and vice versa. This result holds despite the fact that it is impossible to predict which set of measurements will be observed. As a result, measurements performed on one system seem to *instantaneously* influence the other system entangled with it—regardless of how far apart they are.

Now let the second particle be a black hole, then we seem to have an analogous case of "spooky action-at-a-distance" that is somehow brought about by the two objects being entangled. Hence the mystery of the anticipatory black hole seems identical to the mystery of entanglement in general.

6 Moved by Applied Forces or by Choosing Best Next Step

Nineteenth century mechanics formulated particle motion paths in two ways: in differential equations that expressed Newton's laws of motion and gravitational attraction and in Lagrange's integral equations that expressed Hamilton's principle of stationary (i. e., "least") action. Newton's laws explained motion by means of forces applied to the particle, step-by-step (i.e., dx/dt-by-dx/dt), from an agency located in the environment (and assumed in the initial conditions). In contrast to Newton, Lagrange explained a particle's motion by integrating the difference between its kinetic and potential energy (a quantity called the Lagrangian density). Hamilton's principle of stationary action asserts that particles prefer those paths that are at equilibrium along the path of average Lagrangian density. This is the so-called "least," or better, *stationary action path,* as compared to all other paths along which action (the time integral of energy) never changes (hence, the term stationary action path).

Lagrange's action integral method always yields a path that satisfies a condition known as the Euler-Lagrange equation and that coincides with Newton's solution. The two methods are formally equivalent, in the sense that they always give the same particle trajectory as their solution, and, as we shall see, they both entail the involvement of intentionality in their dynamical explanations. Let us see what this means.

If a particle is pushed by Newtonian forces applied to it from the outside, agency is externalized such that the particle has no choice but to move as made to. By contrast, if a particle must find which path out of all possible paths is the least action path, then it seems to require a particle to make choices. Thus it seems that it has intentions. For this reason, Poincare' (1952) called Hamilton's principle "an offence to reason" because it apparently anthropomorphizes particles by requiring that they choose so as to satisfy a criterion (i. e., exhibit an intention). Furthermore no mechanistic explanation has ever been given for how a particle is able to do this intentional task.

Physicists have typically expressed their chagrin at the apparent need for a particle to consider its choices, especially when only the Newtonian path is considered real—the Lagrangian defined paths being mere possibilities, mathematical fictions, and thus not to be numbered among the physical entities populating the universe. For not being actually allowed by the laws of nature, how could they have any real status even if particles could choose. Such choosing would be nonphysical since it allows them to violate conservation laws. Hence no particle can have such freedom! But still they seem to. Another mystery!

In spite of this apparent absurdity, a closer look at both Newton's and Lagrange's mechanical accounts shows them both to be riddled with intentions.

7 A Pox on both of your Houses

Why then do physicists not simply stay with the Newtonian account to avoid such particle chicanery? One reason is that this account has its own problems. If the particle only goes where external forces make it go, how do the external forces themselves get directed? A regress to the most prior initial conditions seems unavoidable (like Aristotle's prime mover regress). Could initial conditions not be explained as the product of prior application of the laws? It seems not, for initial conditions are complementary to dynamical laws in the sense that not only can they not be explained by such laws, but are needed if the laws as stated in their general form (differential equations) are to be made specific to a given situation. Without the initial conditions, the laws have no power of prediction or explanatory relevance (Pattee, 2012).

Even if we assume the particle were a free agent, how could it make such choices? It would need to be enveloped in some kind of information field that informs it about the best next step to take. But then it must possess an information detection system and some means to act in a self-controlled manner. But this requires particles to have complex interiors that house *inter alia* an on-board action potential and a control mechanism that allows it to be guided by that information along its intended goal-path. This is of course contrary to fact.

For particles with simple interiors, such as electrons and photons, are known to abide by Hamilton's principle and to follow stationary action paths (if not constrained to do otherwise). For this reason, Poincare's objection to Hamilton's principle seems quite reasonable—even though the principle has never been abrogated in nature. Thus there must be another story that honors both Poincare's reasonable objection and Hamilton's valid principle. There is. And it is called Feynman's "sum over histories" approach to quantum physics. We consider it next.

8 Deriving Hamilton's Principle from the Sum over Histories

Feynman's strategy was to treat the behaviors of particles as following probabilistic waves rather than simple trajectories (Feynman & Hibbs, 1965). All possible paths are allowed, even non-physical ones. Through constructive and destructive wave interference (or positive and negative phase correlation), the set of possible trajectories is "sculpted away" until just those paths remain which are as close to the least action path as Heisenberg's Uncertainty Principle would allow. Hence the path selected is not where the particle *actually* is but where it is *most likely* to be found. The outcome of this move to quantum field theory is that the particle is constrained to follow the path left standing after all other paths have been cancelled by phase interference. In this way, the least action path simply emerges from the pack, therefore, making it *unnecessary for the particle to select its own path*. A law of nature does the choosing.

Here, however, determinism (simple location and certainty) is traded off in favor of a tolerable degree of indeterminism (distributed location and uncertainty). As a result this approach succeeds in removing the "offense to the reason" that so bedeviled Poincare' and others. In other words, the particle need not choose its path because it is constrained to follow the preferred path automatically.

Although the experts agree that the process works and even allows the other quantum strategies to be derived from it, whether it is physical or just mathematical is still an open question. Even expert physicists were perplexed by Feynman's suggestion that phase interference somehow acted simultaneously across all possible paths to automatically find the particle's preferred path. An anecdote told by one expert reveals how incredible Feynman's claim seemed to most physicists at the time and to many even today (Dyson, 1980).

> Thirty-one years ago [1949!], Dick Feynman told me about his "sum over histories" version of quantum mechanics. "The electron does anything it likes," he said. "It just goes in any direction

> at any speed, forward or backward in time, however it likes, and then you add up the amplitudes and it gives you the wave-function." I said to him, "You're crazy." But he wasn't. (p. 336)

It is now generally conceded that Feynman's method is so fundamental that all other forms of quantum theory can be derived from it. Also, it has been shown to be useful throughout a wide domain of physical phenomena.

A major difficulty is encountered however when we try to understand how Feynman's path integral does its job without violating the dictum that nothing (with non-zero resting mass) can travel faster than the speed of light. It would seem therefore, according to Feynman's own words, that the particle must check each path in its entirety before choosing the right one—quite an impossible task, unless it could do so instantaneously in disregard of the relativistic limits (i. e., speed of light) placed on causal action. Perhaps, it is just one more weird aspect of quantum theory to be tolerated. In any case, we have found it a useful tool for understanding intentional dynamics of any system—whether inanimate or animate.

It is important to note that Feynman's "mechanism" of phase correlation postulated to explain Hamilton's principle is not a causal principle. It operates through a kind of wave interference process across all possible paths at the same time. In fact, no one knows quite how to interpret the mathematics physically. There is agreement however that it works but it remains a mystery by what physical principle it does so. Could it be that this is just another case of intentionality in physics and that intentionality lies at the root of the mystery?

9 Ecosystems have Current States Entangled with Goal-states

> "There is no classsical analog for a system whose full state decription contains no information about its individual subcomponents" (Susskind & Friedman, 2014, p. 231).

> "Information about self accompanies information about the environment, and the two are inseparable . . . like the other side of a coin. Perception has two poles, the subjective and the objective, and information is available to specify both. One perceives the environment and co-perceives oneself " (Gibson, 1979 p.126).

Consider a simple example. Certain pairs of systems are relational in the sense of being so inexorably related and mutually dependent that they can not be separated without losing something essential to their identity. For instance, one can not be a husband without having a wife. Mathematically, a variable cannot be a conjugate, x, without having a shared identity with another variable, y, such that together they are arguments of a conjugation operator, $(xy)^* = yx$. Here the $(xy)^*$ term is an operator that inverts the terms. More generally, the schema ( )* can represent an abstract operator that inverts the order of any two things whatsoever (of the right kind) but with the caveat *if and only if* they have the same relation to the conjugacy operator. Consider the examples, (AB)* = BA, or (up down)* = down up.

So it is with entangled pairs, there must be an entanglement-making operator that defines their shared identity. In quantum physics that operator is interference, or better, is *interferes with*. Remarkably, any two objects (of a certain kind) that were ever together will continue to be co-identified regardless of how much time or space separates them. With respect to ecosystems, in this context, *organism* (O)-*environment* (E) systems, the O and E components share a kind of conjugacy relation—what E affords x for O if and only if O has the means for doing x. This is consistent with the Gibsonian concept of *affordance* (roughly, what use something has for an actor) and its dual *effectivity* (roughly, the actor's action of using it) (Shaw & Kinsella-Shaw, 1988).

One of the chief characteristics of intentional dynamical systems that make them somewhat nonintuitive is their quantum-like inability to be broken down into smaller, more easily analyzable parts. Hence reductionism, a favorite and useful method for most sciences, especially classical physics, is inappropriate. Let's assume the subsystems, O (e. g., a particle, system, organism) and E (i. e., environmental context), are the entangled components of an ecosystem. Thus they can not stand alone because information about one is also information about the other, that is to say, they are contextually bound together because they have entangled states. They are distinct but inseparable. Mathematically speaking, such systems are said to be *non-factorizable*. The two subcomponents, O and E, are stuck together by shared interference terms. Let's take a moment to consider this claim in more detail. Specifically, in the next section, we consider the origins of entanglement.

10 Interference, Complex Numbers, and the Origins of Entanglement

What exactly makes quantum systems seem so weird as compared to the more intuitively comprehensible classical systems? Actually, the source of the weirdness is perfectly clear, so clear, in fact, that it is taught in every introductory course in quantum physics—even if the weird consequences may continue to boggle intuitive comprehension. The source resides in the difference between classical probability theory and quantum probability (amplitudes) theory. The main difference is that while classical probability theory is based on the familiar real numbers, quantum probability is instead based on complex numbers. In this matter, as Dr. Samuel Johnson admonished, although I can promise you an explanation, alas, I cannot promise you an understanding. For it is candidly admitted by experts in the field that they too find it difficult to understand.

> "Those who are not shocked when they first came across quantum theory cannot possibly have understood it."—Niels Bohr
>
> "I think I can safely say that nobody understands quantum mechanics"—Richard Feynman

Let A and B be mutually exclusive events, say, as observed with respect to the slits in the famous double slit experiment. In classical probability theory, they would have associated probabilities PA and PB, so that the total probability of them occurring is obtained through simple addition:

$$P_{A \cup B} = PA \ + \ PB.$$

Contrast this with quantum probability, where, instead, their complex number amplitudes add such that extra terms are produced:

$$P_{A \cup B} = PA \ + \ PB \ + \ (\Psi^{*}A \ \Psi B \ + \Psi A \ \Psi^{*}B) = |\Psi A \ + \Psi B|^2$$

There is an extra term, yielding physically different behavior. Also, for the right choices of ΨA and ΨB, you could end up with two events that have nonzero individual probabilities, but their probabilities sum to zero! Or, alternatively, they sum to a value higher than the individual probabilities.

To appreciate how the interference terms come about, consider the familiar example of squaring a two variable sum in simple algebra.

$$(x + y)^2 = xx + \underline{xy} + \underline{yx} + yy,$$ where xy and yx are interference term analogs.

Notice how the squaring operation introduces, in addition to the self-multiplication of each variable separately, two mixed cross terms (underlined). If we are dealing with complex rather than real numbers, then the order of the variables in the cross terms cannot be inverted, i. e., $xy \neq yx$. However if we are dealing with real numbers, and since real numbers are their own conjugates, then *xy* = *yx*.

Probability amplitude for entangled events is:

$$p(S \text{ or } T) = |A(S) + A(T)|^2 = |A(S)|^2 + A(S)A^*(T) + A^*(S)A(T) + |A(T)|^2$$

Notice the formal analogy between the equation above for the quantum probability amplitudes of an entangled pair of systems, S and T, and the equation below for the quantum probability of the entangled subsystems of an intentional dynamical ecosystem, O and E. The analogy is made explicit by a one-to-one substitution of O for S and E for T, and noticing that the typographies of the two equations match perfectly.

$$p(O \text{ or } E) = |A(O) + A(E)|^2 = |A(O)|^2 + A(O)A^*(E) + A^*(E)A(O) + |A(E)|^2$$

To make the proposed analogy even clearer, we expand the squared terms to their product form:

$$|A(O) + A(E)|^2 = |A(O)A(O)| + A(O)A^*(E) + A^*(E)A(O) + |A(E)A(E)|$$

(Here * indicates conjugation so that the A and A* are conjugates, in the usual way for complex numbers, i. e., a + ix and a – ix.)

Figure 2 shows the interference equations in digraph form. The strongly connected pair of systems can be used to portray the mutual dependence of O and E during a "perceiving-acting" cycle where there is perceptual guidance of actions (e. g., One perceives in order to move, and moves in order to perceive). The perceiving-acting cycle, in the present context, plays the role of the goal-path propagator as in the Feynman's "sum of histories" path integral (Feynman & Hibbs,1965). In Figure 2, the arrows are given a *dual* interpretation; they represent the interplay of both information and control as conjugate operators. For simplicity, we show just one—the primal—of the two digraphs. The dual digraph is obtained by reversing the arrows on the primal digraph. (Elsewhere, we have discussed in detail this 'model' of an ecosystem under the auspices of Kalman's famous duality theorem (Kalman, 1960) for adjoint systems (Shaw et al, 1992) and, alternatively, as a Lie group (Shaw et al, 1990).

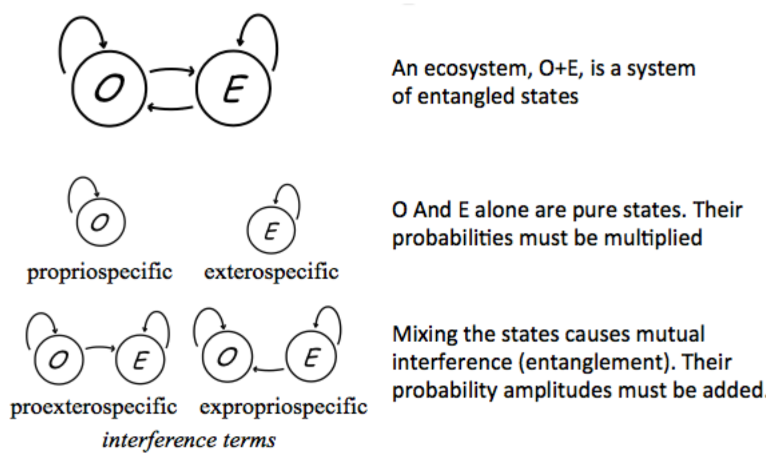


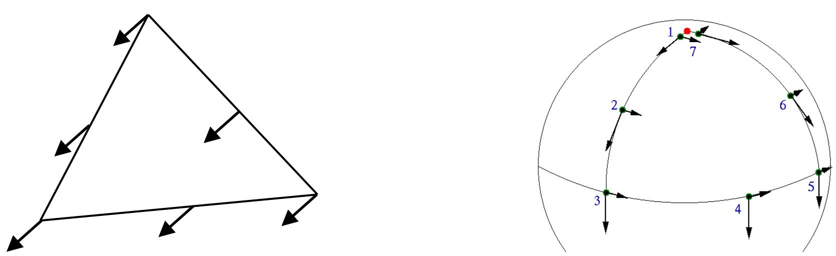
Figure 2: Digraphs showing an ecosystem (top), the O and E subsystems (middle), and the interference terms (bottom). Terminology: *propriospecific* refers to information (or control) for an O independent of E; *exterospecific* refers to information (or control) for E independent of O; and *proexterospecific* and *expropriospecific* refers to how O interacts with E and how E interacts with O, respectively. For our purposes here, the type of interaction is construed as interference. Again notice how the digraphs fit both interference equations by the simple substitution, as before, O for S and E for T. As stated earlier, the interference terms carry the entanglement of the two systems in both the physical and ecological case.

11 Gauge Forces and Cascade of Entanglements

As mentioned earlier, widely separated pairs of particles (or systems) that initially interacted can become entangled. If so, they will exhibit what is called *quantum* correlation. Recall that this means they are no longer separate individuals but must be treated as different aspects of the same entity. Where ordinary correlation is linear, quantum correlation is nonlinear. The nonlinearity arises from the entangling process. And we saw how an ecosystem is also formed by the interaction of two systems, say, O and E, which coalesce into an inseparable whole, O+E, because they share states. When such coupling is strong, it is synonymous with being entangled—although we should bear in mind that there may be degrees of entanglement—a useful fact when dealing with learning or tuning. What is so interesting about entanglement? Here is the standard reply:

Being entangled bestows upon the system of compounded states a nonlinearity in phase correlation not previously there (hence the term "quantum" correlation). This added phase factor is conventionally called a "geometric" (or Berry) phase because it arises from a geometric property of the manifold (e.g., its curvature) on which the system's actions take place (such as moving from place to place). Since the added phase factor is *kinematic* in nature rather than kinetic, it leaves the energetics of a system untouched, and thus can be accrued by any system whatsoever.

Beginning with Einstein, the origin of the geometric phase factors is usually illustrated by showing how a frame-independent covariant derivative is needed to define a *connection* (a way of transporting in parallel fashion from one location to another on a manifold) that ordinary calculus cannot handle. The illustration, Figure 3b shows how a vector moved on a sphere through any closed triangular circuit (whose sides are portions of great circles), fails to return to its initial orientation. The lost orientability is the linear deficiency contributed by the acquired geometric phase and is usually represented as a *bracket product*, or commutator, whose value is other than zero (namely, $[A, B] = (AB - BA) \neq 0$). Moreover, this is also what it means to be *nonholonomic*.



(a) (b)

Figure 3. Dynamic versus Geometric Phase. (a) A vector is parallel transported (without rotation) around the triangular circuit on a flat plane with no loss of orientation. But compare to (b). Here the spherical triangle consists of three arcs of great circles. A vector is also parallel transported (without rotation) around the circuit by a *covariant derivative* from position 1 to position 7 always pointing in the same direction—toward the South pole. But notice when it returns to initial position (where 7 = 1) at the North pole, it has a different orientation yet no forces have been applied to rotate it. Because its change in orientation is due only to the curvature of the spherical surface and not to forces, it is called a change in *geometric phase*. Here a very important concept is introduced into modern physics—that of *gauge force*.

Imagine a system moving along a goal-directed path (an intentional connection) accrues a geometric phase from the curvature of the manifold on which its actions are defined. Also, assume it appears to have rotated from its initial goal-directed state. The goal-relevant information is a *global* variable while its apparent rotation (geometric phase change) is a *local* variable. To return to the intended goal direction (as globally specified) requires that the actor counter-rotate (locally) so as to cancel the effects of the acquired geometric phase. Since the actor has mass, to make the correction calls for application of a real torque force. Thus the corrective force was specified geometrically but applied kinetically. This is what is meant by a *gauge force*. In this way we see how information and control operators that define the perceiving-acting cycle, or propagator, are duals—as illustrated by the digraph earlier (Figure 2).

The long range aim of our program will be to elaborate on the meaning of the following two general hypotheses and to justify their claims:

> *(i) The actions of an ecosystem are controlled by gauge forces and specified by gauge information.*
>
> *(ii) Intentional quantum dynamics is a positive process of entangling or negative process disentangling states of O and E—all in the service of keeping to an intended goal-path*.

(NOTE: The loss of orientability is due to the system having moved along a *causal connection*, while the correction that cancels the geometric phase so accrued is a controlled, counter-directed torque force applied along an *intentional connection,* i. e., goal-path, intended to remove the accrued phase.)

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Note again how the four information-control forms look analogous to the interference equations (Figure 2). This should mean that they are also, formally speaking, evidence that O and E interfere with each other—evidence that they are generally quantum correlated, and therefore entangled. This means they are inseparable subcomponents of the unfactorizable ecosystem to which they belong. The ecosystem also comprises a set of superposed dual states—the affordances of E that O may choose as goals to realize and the effectivities of O that produce the actions, or means, to realize them. In the past (Shaw & Turvey, 1981), we have stressed that ecosystems are coalitions of dual pairs of dual operations, symbolized by '<>', at various scales:

E <> O ⊃ *affordances* <> *effectivities* ⊃ *perceptions* <> *actions* ⊃ *information* <> *control*

Now we want to amend that formal description by recognizing that the dualities that tied these items together are actually just examples of entanglements, at different scales, from most inclusive, to the least inclusive, that bind E and O together as an ecosystem.

(a) E <> O:	*system* entanglement
(b) effectivity <> affordance:	*function* entanglement
(c) perception <> action:	*process* entanglement
(d) information <> control:	*state* entanglement

These are the potential levels of entanglements that make an ecosystem a quantum dynamical system.

In bringing macroscale intentional dynamics into microscale quantum theory, have we jumped too many scales? Is there a danger that entanglements, even if they existed, might be destroyed? The entanglements postulated here however are not among massive objects or even ordinary states of such, but between intentions, information, and control state influences. The strength of these influences could be very, very small—perhaps, even Planckian scale. And might not the brain-cns processes involved in intentional dynamics be quantum scale as well (say, as argued by quantum brain dynamicists Jibu & Yasue, 1995)? If so, then the problem that might arise when skipping scales does not even arise. Also, in the theory and practice of quantum computation, all the qubit states are instantiated on macro-scale machines—so why not on the brain-cns system as well? Another example of the play of quantum dynamics at the macroscale is revealed in contemporary theories of friction—especially in the case of miniaturization.

Finally, to make the system capable of intended goal-directed behaviors, that is to say, to make it an intentional quantum dynamical system—we must also give it the freedom to make (creation operator) and break (annihilation operator) entanglements. Intentions, goals, and goal-paths are derivative of the entanglement possibilities already mentioned. Potentially, we see in this strategy a way to redress the long-standing conundrum of temporally "backward" causality in accounts of goal-directed behavior that rely on both local classical mechanism (i.e., causal connections) and nonlocal gauge mechanism (i.e., intentional connections). Correspondingly, we see in the move to a quantum intentional dynamics better prospects for a physically lawful account of goal-directed behavior at all scales of nature.

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