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Hints of Intelligence From First Principles

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Are intelligent systems necessarily biological or might they be only physical? We propose that a system be deemed intelligent if its actions exhibit intentional dynamics. A lower bound on intelligence appears in such diverse physical systems as black holes making anticipatory adjustments to approaching matter and particles choosing among myriad possible steps the next least action step. While thermodynamic laws are known to govern black hole dynamics and cosmological evolution, we show their role in intentional dynamics is analogous—suggesting a new field of intentional thermodynamics. Perhaps systems are intelligent if they conserve the action potential identified by intentional dynamics—one comprising information and control as interacting duals. Hence a foundational mini-max principle is proposed, namely, that the rate at which entropy production is maximized varies inversely with the rate at which this action potential is minimized. Intentional thermodynamics' geometry is shown to be a path space whose solutions are goal-paths, i.e., paths that conserve the action potential. Finally, we ask if physical intelligence might not have been produced during the Big Bang.

HINT 1: A LOWER BOUNDARY FOR INTELLIGENT ACTIONS

What makes a system or process intelligent? Because no consensus exists on what intelligence is, this is a moot question. To get off ground-level zero, one needs to take a stand. A suggested working hypothesis is that anything with

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certain dynamical properties (to be described), whether it is a "thing" or a life form, will qualify as intelligent. Two physical scenarios are examined—two apparent violations of causal law—that seem to hint at a lower boundary of intelligent actions.

Intelligent Particles

Poincaré (1905/1952) argued that the assumption of the principle of least action by which one passes from force-based mechanics to a potential (energy)-based mechanics involves an "offense to the mind." He strongly objected to Hamilton's ("least" action) Principle (1834/1935) because he thought it forced an anthropomorphic interpretation on how a particle chooses the next step along a path. Newton's (1687/1999) lawful explanation was less objectionable because it was framed in terms of forces and thus required the particle to make no such intentional choices. A differential equation characterizes a particle's next step as a forceful push from behind. By contrast, a lawful explanation in terms of a path integral is not causal but anticipatory. By taking the form of an integral (path) equation the particle, Poincaré argued, apparently must "choose" from among many possible next steps the one that minimizes the action (work done over time). Such an analysis replaces Newton's initial conditions, where a force is applied to move the particle ahead, with the idea that the particle instead moves ahead because the action *will be* least in some direction rather than others.

The danger that this variational approach to mechanics might tempt theorists to anthropomorphize particles is still recognized today. Feynman, who developed a version of quantum mechanics that addresses this issue, echoed Poincaré's (1905/1952) concern this way:

> It isn't that a particle takes the path of least action but that it smells all the paths in the neighborhood and chooses the one that has the least action by a method analogous to the one by which light chooses the shortest time. (Feynman, Leighton, & Sands, 1968; p. 9)

A more recent restatement of the problem asserts the following:

> The mechanism by which the particle selects the physical trajectory of stationary action is not at all clear. The initial velocity is not given, so that the particle will not "know" in which direction to start off and how fast to go. It is not clear how the particle can "feel out" all trajectories and "choose" the stationary one. It should be kept in mind that classical physics does not recognize any path other than the stationary path. Thus, out of a whole set of "nonphysical" paths, introduced a priori, the classical principle of stationary action selects a unique physical trajectory through some mechanism which is not readily apparent. (Narlikar & Padmanabhan, 1986, p. 12)

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Feynman admitted that a prime motivation for developing his own "sum over histories" (path integral) approach was to remove these objections to Hamilton's Principle and to put it on a sound physical basis (Feynman & Hibbs, 1965). He replaced the "next step" choice problem that so confounded Poincaré (1905/1952) with a "next path" problem where the choice is made automatically by a phase correlation "law." Those paths that are out of phase eradicate one another through destructive interference, whereas those that are most in phase, through constructive interference, sum to the path that agrees with both Newton's causal principle and Hamilton's least action principle. Where did the particle's intentional choice go?

Unfortunately, this is not the end of the story. The phase correlation "mechanism," like all correlations, acts instantaneously over paths in violation of causal law and so is "unphysical." Also, it is unfortunate that the mathematical foundations of Feynman et al.'s (1968) path integral remain obscure—although neither of these demerits has detracted from the practical value of Feynman et al.'s approach for many domains in physics.

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Intelligent Black Holes

Here is another case of apparent violation of causal law that seems to demonstrate a modicum of intelligence. When a particle traveling close to a black hole is swallowed, the black hole necessarily increases in volume. How it increases, however, is problematic. Just as the Hamiltonian particle seems to anticipate each next step to find the one that keeps action minimized (or stationary), so the black hole seems to make an anticipatory response to the approaching particle to keep both discrete quantum physics and continuous relativity physics satisfied. To explain this strange phenomenon required recognizing that two horizons rather than one must cloak the black hole singularity. After many years of debate, the following account became the consensus view (Thorne, 1994).

The apparent horizon (the outermost location at which outgoing photons are being pulled inward) jumps outward suddenly and discontinuously to accommodate swallowing the particle as quantum theory demands. But, also, in advance of the particle's arrival, the *absolute horizon* (the boundary between events that can and cannot send outgoing photons to the distant universe) starts to expand *before* the hole swallows the particle. That is to say, it expands smoothly and continuously in advance of the matter's arrival, as demanded by general relativity.

Normally, when a system exhibits prospective control by giving an anticipatory response to something that has not yet arrived, information is present to specify the oncoming encounter. This is similar to when an infant begins closing her hand in preparation for grasping an approaching object that she sees or when an automobile driver begins putting on brakes before reaching the stop sign. However, in these and other cases like them, anticipatory behavior is only possible when information about the upcoming events is detected to give an early warning. Without the information, there is nothing to evoke the anticipatory response. To claim the black hole detects information specifying the estimated time of arrival (ETA) of the approaching particle is egregiously to anthropomorphize the black hole. But is there any alternative explanation for how a system might exhibit anticipatory behavior without having to detect information and choosing to respond to it? Perhaps.

HINT 2: BIOLOGICAL AND PHYSICAL CHOICE

Terminological distinctions are introduced that help isolate the meaning of "intelligence from first principles." The focus is behavior at a choice-point. Biological and physical examples are given.

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Focusing Intelligent Actions

If we allow the phrase *biological intelligence* to mean "biological systems that exhibit intelligent actions," then the corresponding phrase attendant to a quest for intelligence from first principles would be *physical intelligence.* Its corresponding meaning would be "physical systems that exhibit intelligent actions." Phrased this way, *type of system* is separated from *intelligent actions*. Also, by calling actions "intelligent" it seems natural to infer that other actions might not be intelligent. "Biological" and "physical" denote the *kind of embodiment* of the system in question.

By setting up the terminological distinctions this way, the natural implication is that intelligent functions do not belong exclusively to either biological or physical systems. And, because biological systems are also physical systems, there is the natural implication that being intelligent is not the sole province of living systems. Thus if we allow that biological characteristics might be ignored, then we must ask what is it about the physical embodiment that allows its actions to be presumed intelligent—the implication being that we might ignore those physical properties that are not necessary to the intelligent actions.

In this way an obvious fact is made doctrinal: Biological systems are as legitimate cases of *physical* intelligence as are strictly physical ones. Core principles of physical intelligence are equally present in both. To be discovered is whether biological principles are other than physical or physical of a different order.

Following this line of reasoning to its logical conclusion, we must ask whether the physical principles that underwrite the intelligent actions might not be separated from the physical principles that do not. Of course, we must recognize the possibility that intelligent actions are underwritten by *all* of physics whereas the unintelligent actions are underwritten by something less. *Now here is the* *point:* Could it be that all intelligent systems, living or nonliving, have in common the very same physical principles? We present two examples of very simple intelligent functions—one logical, the other geometrical.

Simplest Intelligent Choice

A dog chases a rabbit down a woody path. The path curves so that the dog loses sight of the rabbit. Around the curve the dog encounters a fork in the path. Did the rabbit go right or left? The dog, not knowing which, randomly chooses left. If the dog smells the rabbit down the left path, he continues to chase the rabbit. But if the dog fails to smell the rabbit down the left path, he quickly aborts and switches to the right path—a clear instance of logical intelligence.

Consider the similar situation of a programmer who is trying to locate one final, elusive "bug" (error) in a program. The programmer has determined that the bug must exist in one of two parts of the program. With additional debugging, the programmer is able to rule out one of the parts. Without additional checking, the programmer concludes that the bug exists in the other part of the program—also a clear instance of logical intelligence.

The apparent similarity between the dog's "reasoning" and the programmer's suggests there is a common pattern. If A and B designate two alternatives, both "arguments" are instances of the general pattern of the exclusive disjunctive syllogism—among the simplest argument types:

Premise: Either A or B,
Premise: not A,
Conclusion: Therefore, B

An Impossible Choice

We speak loosely of the "least" action path, or extremum path, when what Hamilton's Principle actually picks out is the *stationary* action path. This is the path along which the action remains constant and not necessarily where the action is "least" (or "most"). For example, compare the action of three particles moving on the surface of a sphere. The first particle follows a great circle path, the second follows a minor circle path, and the third a path that crosses back and forth over the great circle. The great circle path is longer than the minor circle path and shorter than the back-and-forth path, and hence not an extremum, but still is the stationary action path. What counts in determining the action value is not path length per se but which path has the most constant curvature, and this, of course, is the geodesic of the surface. For it is along a geodesic, and only a geodesic, that action is constant in the sense of no speeding up or slowing down due to change in direction.

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Now assume a "free" particle is placed on the surface of a sphere. Any point the particle occupies is a choice-point from which a potentially infinite number of paths emanate. According to Hamilton's Principle, the particle must somehow choose from among the myriad paths a path that follows a great circle route. How can it make such a smart choice? To do so, the particle must have access to global information that specifies the surface is a sphere rather than some other shaped surface with different geodesics. Unfortunately, such information is not available at a differential (infinitesimal) locale where the manifold (surface) is defined as flat (Euclidean). Because all neighborhoods of a point are alike (flat), how does the particle choose the right path? Even if it were present, how would the particle being so simple use such information?

The "Hole Argument"

A choice-point encountered by a particle along a path disrupts the particle's goal direction by presenting an enormous number of indistinguishable *next path* opportunities. Mathematically, a choice-point is a nondifferentiable singularity—a nonholonomic (nonintegrable) region wherein the dynamical laws cease to apply and cannot be reinitiated (because the Cauchy initial value problem becomes ill posed). For the particle's path to keep the action stationary the laws must be invariant (actually covariant) over all regions of the path manifold; there can be no "holes" in the laws' coverage.

General covariance (or diffeomorphic covariance) is invariance of the *form* of physical laws under arbitrary coordinate transformations. Einstein originated the "hole argument" in his effort to validate this principle (Stachel, 2002). Consider a space–time filled with matter except for one region, the hole, which is empty. He wondered if a full specification of both metric and matter fields outside the hole would fix the metric field within the hole. He had expected that his tensor expressed laws would be covariant in the sense of applying to all regions of the space–time manifold—even holes. To his disappointment, all of his mathematical arguments failed to confirm this hypothesis: what takes place outside a hole cannot tell us what takes place inside the hole.

Any system faced with a choice is susceptible to the "hole argument," such as a black hole "choosing" when and how much to expand in anticipation of swallowing an incoming particle. This means laws that apply to the (global) environment of a system (e.g., black hole) cannot provide insight on what happens to that system at the moment it occupies the (local) choice-point singularity (the hole). One might ask whether nature employs some undetectable subterfuge outside the province of causal law. Could "choosing" be a process governed by symmetries more profound than causal laws?

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HINT 3: INTELLIGENCE AS A CONSERVATION

Intelligence, like momentum and energy, might also be a kind of conservation (a symmetry) that is the generator of intelligent actions. If so, the form intelligent actions would assume is that of the extremals (stationary action paths) characteristic of the underlying symmetry, which would then define an equivalence class of intelligent systems, both living and nonliving.

Locating Intelligence

Attribution theory would locate the seat of intelligent actions in an intelligent actor. Neurocognitive psychology would locate it in the actor's brain. Neither is helpful if we expect to locate intelligent actions in the interactions of nonbiotic physical systems with their physical environments. On the other hand, if we assume ecological psychology is a particular domain of ecological physics and ecological physics a particular domain of general physics, then the most rational, appropriate, and obvious scientific approach to intelligence from first principles is ecological physics. Any progress made on the problem in this way would also be progress toward an ecological psychology of general intelligence for both living and nonliving systems.

Symmetries and Conservations

Where do intelligent actions come from? What makes them different from other actions? What makes translations different from rotations? Or, even more fundamental, why should there be translations and rotations at all? No transformations in physics are arbitrary. Rather, as Emmy Noether's famous theorems demonstrated, they are generated by dynamical variables with symmetries that are associated with conservation laws (Neuenschwande, 2011). The invariance of a system under transformation implies the conservation of the associated generator. For instance, conservation of linear momentum is the generator of spatial translations, conservation of angular momentum is the generator of rotations, and conservation of total energy is the generator of temporal translations. Is there a conservation of some dynamical property that is the generator of intelligent actions? If so, then our goal of intelligence from first principles becomes a well-posed problem and not just a diffuse aim.

Our task is to identify the conservation that brings intelligence into the world. How big an order this might be depends on what types of dynamics we might identify beyond those ordinarily recognized, such as classical mechanics, relativistic mechanics, and quantum mechanics, which so far have proven unfruitful in this regard. Because of this lack, the mind-matter dualism issue will simply not go away but remains a red herring that misdirects and wastes scientific resources. A successful account of intelligence from first principles would make mind–matter dualism superfluous.

Intentional dynamics (previously called ecomechanics) is a mechanics defined at the ecological scale. It is our candidate for a new and, we think, more appropriate mechanics of purposeful action (Shaw & Kinsella-Shaw, 1988; Shaw, Kugler, & Kinsella-Shaw, 1990). This ecological approach to intelligence from first principles would locate intelligence as an intrinsic property of ecosystems (i.e., context-sensitive systems along with the definitive context). But there is groundwork to be laid before considering this approach.

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Questions About Extremals and Markers

What do you do when you do not know whether what you are looking for exists or what it looks like if it does? It is worse than searching for a unicorn, for even there you know what class it belongs to (horses), and the horn is a marker that distinguishes it from other horses. Unfortunately, in the case of an intelligent system's extremals (i.e., goal-paths of stationary action), we do not know the class to which they belong, and even worse we know of no marker that distinguishes them from other extremals in their class. But we can take a stab in the dark and hypothesize under which class of extremals an intelligent system's extremal is most likely to be found.

The dynamics of any particle or system propagates extremal paths characteristic of the dynamics but nonspecific to the particular properties of the particle or system involved. Here is the key: *The action of any dynamical system is conserved along extremal paths that leave invariant certain symmetries characteristic of the system.* For example, structural morphology, whether biological or geological, develops along gravitational field lines tailored to genetic constraints (symmetries), on the one hand, and hydrodynamic symmetries (e.g., erosion) on the other. In general, physical phenomena develop along paths of stationary action sometimes called *Hamiltonian extremals*, whereas optimal control systems do so along similar paths known as *Pontryagin extremals* (i.e., paths satisfying Pontryagin's Maximum Principle; Torres, 2001). The nature of the extremal is a function of the characteristic action left stationary by the system: different action, different extremals. Most noticeable are differences in the extremals of free particles versus those of controlled particles. If intelligence is a constraint (a symmetry), then we might expect that the action extremals produced by intelligent control would be distinctive in some way from those of particles free of such control.

Answering the question, "Along what extremals would an intelligent system's action unfold?" depends on our ability to broaden the conception of dynamics from classical mechanics to ecomechanics. Hence the most germane question is what distinguishes extremals for intentional dynamical systems. Putatively, *identifying the symmetries preserved along these extremals will tell us what intelligent action is.*

Particles Exhibiting Intentional Dynamics

A free particle moves effortlessly from an initial condition to a final condition along extremal paths that keep Lagrangian action stationary, that is, are solutions to the Euler-Lagrange equation. Metaphorically speaking, this is a smart way to travel because it is most stable and efficient, requiring the least work over time. A constrained particle, however, moving between the same initial and final conditions might travel paths other than extremals. Although such paths are not ideal, the satisfaction of the constraint means the particle travels by way of a *constrained extremal,* that is, a forced path that keeps the constrained action quasi-stationary, so long as the proper amount of work is done. An applied force must do the work in question needed to keep the particle above the ideal minimum (as that minimum is "intended" by whoever or whatever applies the force). That is, it physicalizes the involved intention and intentionalizes the involved physics, hence the aptness of the term *intentional dynamics.*

Intentional dynamics, like any dynamics, introduces a conserved action quantity called *total generalized action.* This *intentionalized* action incorporates both *goal-specific information* and *goal-relevant control* as defined by a *stipulated goal constraint.* In this dynamics, intention is a *primitive operator* applied by an agent who stipulates the goal constraint, gets the dynamics started, and keeps it moving goalward. In the effort to derive intelligence from first principles, however, intention as the source of the stipulated goal constraint is left unexplained, as is the notion of goal. If we ignore these problems for a moment, then our thesis statement can be formulated. To the earlier question, "Is there a conservation of some dynamical property that is the generator of intelligent actions?" we can now give the following answer: *Conservation of total generalized action is the generator of intelligent actions* (cf. Shaw & Turvey, 1999).

Consequently, if we can find a legitimate physical basis for intention (the primitive goal selection operator), we will have got our fledgling theory of intelligence from first principles off the ground. A question for future consideration will be that of how intentions and goals can be made purely physical (at the ecological scale) so that no ad hoc pyschologistic constructs are needed.

HINT 4: WHERE THE ACTION IS

Action principles play a fundamental role in all domains of physics. Arguably, the action principle as formulated for ecological physics is of fundamental

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importance in establishing physical foundations to intelligence. Indeed, it may furnish such foundations.

The Action Principle

The Action Principle is an important tool for all of science. Here are three reasons for its appeal.

Physical elegance. The Action Principle collects together under one concise heading an unlimited number of diverse instances sharing a common symmetry. Physics allows that a particle could, in principle, follow an unlimited number of paths between two points—Feynman's so-called sum of histories approach (Feynman & Hibbs, 1965). A differential description would specify its motion at every infinitesimal step over every possible path—a fact that can only be summarized in an unfathomable number of differential equations. By contrast, and better, a single action integral will select from the plenum of paths one special path—the stationary (least) action path. Let's look at this in a different way: If a graphing machine traced out on paper a large number of these possible paths, and you were asked to find the path the particle had actually traveled, how would you do so? An effective strategy would be to use the stationary action criterion to select from among the path traces the one that exhibits least variability. This will be the trace of the actual path the particle followed under real-world forces—the path both Newton's laws of motion and Hamilton's Principle would predict.

Physical generality. The Action Principle helps simplify descriptions in physical domains other than just mechanics. Maxwell's (1865) 8 electromagnetic field equations can be replaced by a simple action equation that assigns a single action number describing how the field changes. Similarly, Einstein's 10 field equations for gravity can be summarized elegantly in a simple action formula (Misner, Thorne, & Wheeler, 1973). And Feynman's path integral approach to quantum electrodynamics is also based on the action principle. The main point is that whereas the equations for a given physical domain may be many, a single action equation can offer a concise summary.

Physical unification. The Action Principle helps bring the various fields of physics under a single action formulation. Since the Big Bang became part of the standard theory, physicists have dreamed and worked toward formulating a single universal action principle. One physicist makes this astute observation:

> . . . the world is described by a single action. As physicists master a new area of physics . . . they add to the formula for the action of the world an extra piece

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> describing that area of physics. Thus, at any stage of development of physics, the action is a ragtag sum of disparate terms. The ambition of fundamental physics is to unify the terms into an organic whole. While a mechanic tinkers with his engine, and an architect with her design, a fundamental physicist tinkers with the action of the world. (Zee, 1986, p. 109)

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Ecophysics: Ordinary Physics With Added Constraints

To move from ordinary physics to physics at the ecological scale (ecophysics) does not cost physics anything. To the contrary, physics is enriched. It gains *informational* constraints, *control* constraints, and, most important, *intentional* constraints. With these additional constraints, ordinary physics is broadened to include intentional dynamics as a supplement to the other dynamics.

Ecophysics contrasts with ordinary physics in two basic ways. First, where ordinary physics strives to be perspective-free and to apply at all scales, ecophysics is designed to be perspective-dependent and to apply at specific scales. (This is in the spirit of relational physics; see Rovilla, 1996). Second, where ordinary physics is founded upon an action principle that natural processes do not violate because they cannot, ecophysics is founded upon an action principle that ecosystems can violate but *should not* (if they are to remain adaptive).

To see how the new constraints work in concert with the old constraints, consider the following: Ordinary physics dictates that a free object on earth that falls from a great height reaches its terminal velocity when the gravity force and its drag force (32.18 feet/s^2) balance. A very high impact with the ground is inevitable. Information, control, and intention constraints play no role here. Not so with objects capable of intentional dynamics (e.g., birds, insects, manned helicopters). They can control their lift force in an intended manner. By using prospective control of descent to keep a given variable of optic flow constant, the intended goal of achieving a very low impact vertical landing is assured. Here, unlike ordinary physics where initial conditions are fixed, the initial conditions may be repeatedly reinitialized to guarantee the intended final condition. Thus these additional constraints support context-sensitive modulation of action.

An Action Principle for Ecophysics

Success in performing an intentional task is determined by an ability to pick up the goal-specific information and to use it to initialize and successively reinitialize the goal-relevant control as intended. In this way, an actor is constrained by a motivating intention to pursue a goal by information that specifies the goal-path parameters and by situation-conditioned control parameters. A crucial assumption of intentional dynamics is the notion of a distribution of possible paths. This concept plays a role in ecophysics similar to the role that probability

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distributions and degrees of freedom play in other domains of physics. Contained in the path distribution are all non goal-paths as well as goal-paths.

The term *omega cell* has been introduced to represent a partition of this path distribution, namely, a bounded set of space–time that includes all and only those paths that are goal-paths (Shaw & Kinsella-Shaw, 1988; see Hint 6). Each goal-path corresponds to an instance of a successful performance on a given intentional task. All the paths share initial and final conditions and, therefore, are goal-paths; and most important, each is a stationary action path. When an actor performs a task in the intended manner, a quantity called *total generalized action* (TGA) is conserved over each of the alternative goal-paths (Shaw et al., 1990). TGA could be included in the "ragtag sum of disparate terms" composing the world action equation.

Ordinary action is work integrated over time. As a special case, ecophysical action is the sum of two components: *useful action*, which is goal-directed work, and *useless action*, which is not. The ecological construal of useful action has two further components, the goal-specific action: *control* as the kinetic action (work already done) and *information* that specifies the potential action (work still to be done). Because this ecological (task dependent) form of action involves both information and control components, it can be called *generalized action*; and because kinetic and potential action must be summed, by analogy to total energy, it can be called *total generalized action*. Just as in ordinary physics, where total energy is conserved only in a closed system, so in ecological physics total generalized action is conserved only in an omega cell—the partition of successful goal-specific actions. In this intentional context information and control are dual (adjoint), share a common basis, and therefore are dimensionally compatible.

The foregoing raises a variety of questions that are useful to note here in anticipation of subsequent issues. Is information a concept that might unify our disparate efforts in seeking physical foundations for intelligence? Or, more likely, by coupling information and control, might not ecophysical action prove a better candidate for this job? Might not deeper analysis reveal intelligence from first principles and ecophysical action to be intimately connected—even synonymous?

HINT 5: DUALITY AND INTELLIGENCE

Duality, a kind of nontransitive symmetry, provides the acausal source of efficacy for many physical phenomena. It might play a similarly significant role in the originating of intelligence from first principles.

The idea of duality as a symmetry lies at the core of the most important developments in recent fundamental physics. Over the last 4 decades theoret-

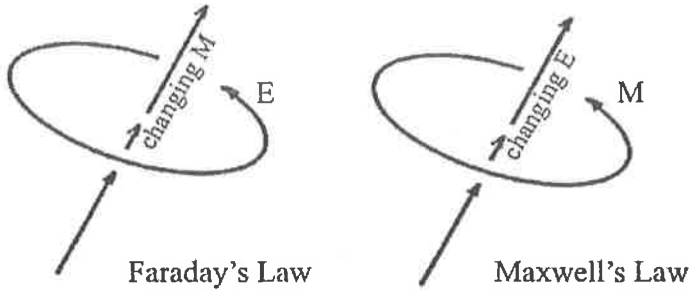

FIGURE 1 The duality holding between Faraday's Law and Maxwell's Law.

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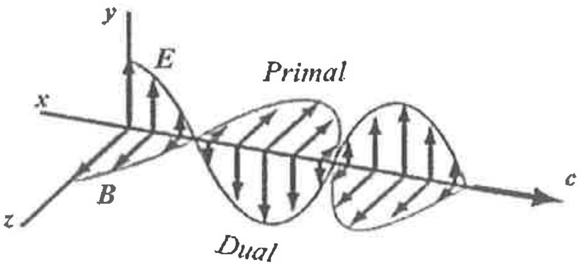
ical physics has found the duality concept useful in comparing many theories and frameworks (Castellani, 2009). Dualities can relate very different physical regimes, with very different ontologies, in a special way: calculations involving variables that describe one regime can be obtained from calculations involving variables that describe the other regime—*while leaving both their physics and ontologies unchanged.* A mapping exists between fundamental components in the formulation of the first system (the *primal* formulation) and corresponding components in the formulation of the second system (the *dual* formulation), and vice versa.

Maxwell-Faraday Duality and Wave Propagation

Faraday's law of magneto-electric (M) induction and Maxwell's law of electromagnetic (E) induction are perfect examples of *dynamic* duals: Faraday's law asserts that a changing magnetic field will induce an electric field whereas Maxwell's law asserts, dually, that a changing electric field will induce a magnetic field (Figure 1). This duality of change is the very heart of electromagnetic theory. The two fields are time codependent—as one rises the other falls in an endless cycle, with the falling of one field being the change needed to induce the rising of the other (Figure 2).



E = electric field magnitude

B = magnetic field magnitude

c = speed of light = E/M

FIGURE 2 The duality holding between the electrical field (E) and the magnetic field (B).

In empty space, where there is no resistance, this motion is presumed to be perpetual and is the mechanism responsible for the broadcasting of radio waves, light waves, and even x-rays across endless empty space. It is important to note that, because of the finite limit on the speed of light, this action continues after its source has ceased to exist—as is the case of starlight reaching the earth and beyond even after the star has ceased to be.

Whereas relational or functional duals are common in mathematics (e.g., geometry, group theory, graph theory), dynamic duals are common in physics: matter and energy, gravity and inertia, fields and currents, waves and particles are examples.

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Kalman Duality and Path Propagation

Two independent systems are duals if their inputs and outputs are in a mutual and reciprocal relationship as shown in Figure 3. To emphasize their temporal duality (i.e., $+t$ dual to $-t$), the control (controllability) and information (observability) components are shown separately.

A primal system (Figure 3) is completely controllable if and only if the dual system (Figure 3 right) is completely observable, and conversely (Kalman, 1960). This means a system constrained at the input, u_1 (say, by goal-specific information), specifies a system constrained at the output (say, by goal-relevant action), and vice versa for y_1. If these primal and dual subsystems comprise the same self-dual system with an on-board potential, then the Kalman duality (like the EM duality for wave propagation) provides the dynamics for path propagation (Figure 4).

Information Detection and Action Control

Several dualities are associated with the system and environment depicted in Figure 5. Of most interest is the dual pair *information detection* ($S \leftarrow E$) and

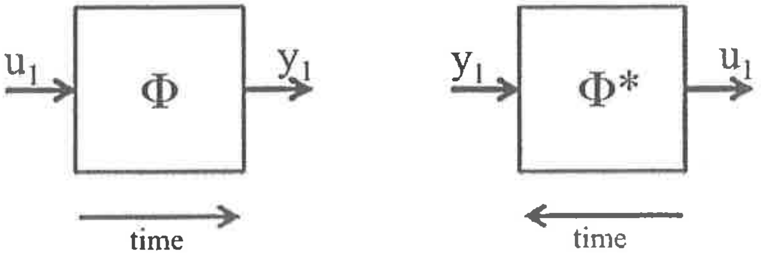

FIGURE 3 The Kalman's duality holding between complete observability (information) and complete controllability (control).

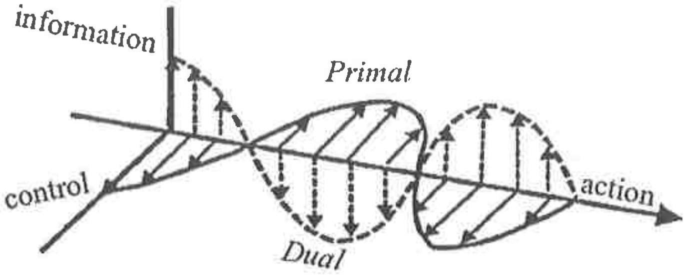

FIGURE 4 The dynamical perceiving-acting cycle consisting of simultaneously present primal (control) and dual (information) components.

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action control ($S \rightarrow E$)—an expression of Kalman's duality theorem. Although the information detection and action control operations are both constantly available, in parallel, over the whole path of travel, their roles as primal and dual swap each time S shifts from detecting the information flow to controlling the information flow, or vice versa. During the cycling, the duals are always compresent and *not* sequential. Figure 5 is not conventional negative feedback and feed forward.

HINT 6: INTENTIONAL THERMODYNAMICS

Seeking intelligence from first principles is most properly construed as an enterprise in intentional thermodynamics. Within this new science one should expect to identify a fundamental connection between total generalized action (TGA) and entropy.

The High Priority of Thermodynamic Laws

Whereas the macroscale laws of relativity and microscale laws of quantum physics are scale specific, the laws of thermodynamics are not so restricted. Their indifference to scale is what makes the laws of thermodynamics necessarily key

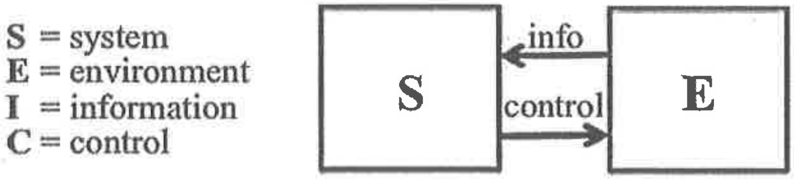

FIGURE 5 An ecosystem comprising an information-control coupling between a system and its environment.

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to the task of determining whether intelligence follows from first principles. As famously suggested by Eddington (1928), thermodynamic laws have priority over all other physical laws:

> If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations—then so much the worse for Maxwell's equations. If it is found to be contradicted by observation—well, these experimentalists do bungle things sometimes. But if your theory is found to be against the Second Law of thermodynamics I can offer you no hope; there is nothing for it but to collapse in deepest humiliation. (p. 74)

Conative Processes in Space–Time

To say that all change in the universe necessarily produces a net increase in entropy is to say that, whatever else it may be, nature is fundamentally and inexorably a *conative* process. Conation is a useful old-fashioned term that gathers together all those processes that motivate and sustain goal-directed efforts. It comes from the Latin *conatus* and denotes *any natural tendency, impulse, or effort that is end-directed.* The hegemony of the Second Law is that at the heart of all systems, great or small, biogenic or artifactual, lie a collection of end-directed processes. If intelligence follows from first principles, then, whatever else the processes constituting intelligence may be, they must also be conative. In more specific terms, intelligence must involve dual defining processes: *entropy production* and (its formal equivalent) *TGA production.* The two covary and, when taken together, they may be regarded as the sine qua non of both intelligence and goal-path propagation.

To be consonant with thermodynamics, physical intelligence must have a dynamics whose aegis covers both intentional and thermodynamical processes. Hence the need for a new term identifying a new science: *intentional thermodynamics*. The suggested foundational proposition of this new science is that *the rate at which entropy production is maximized varies inversely with the rate at which TGA is minimized.* The plausibility of this new science is enhanced by arguments that dissipative systems are describable by a variational (least action) theory (see Badiali, 2005, 2006; Sieniutycz & Farkas, 2005).

Elaborations on the Omega Cell

To interface intentional dynamics with thermodynamics requires a means of partitioning all goal-paths from ordinary paths. An image borrowed from special relativity and applied to the omega cell (see Hint 4) proves helpful. Space–time constraints (e.g., speed of light) restrict all causal processes (including thermodynamics ones), at limit, to a common shape—that of a cone which

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funnels all base processes, over world-line paths, toward an apical end-state (while carrying its ancillary processes along for the ride). To accommodate intentional dynamics, the image must be expanded. The relationship of initial to final conditions can be viewed, similarly, as a pair of dual cones, situated base-to-base, with the right (fore) apex representing the motivating intention and the left (aft) apex the goal intended (Figure 6). This spatiotemporal construct is the omega cell (Shaw & Kinsella-Shaw, 1988).

The omega cell melds the dual cones and marks off a bounded region of the space–time manifold that contains all possible goal-paths that connect both apices. (In Figure 6 only a single representative path is shown.) Such a connection (as Einstein taught us) must, in general, be defined by a *covariant derivative*—a generalization of the ordinary derivative—in order to describe the manifold's curvature induced whenever the system's paths are propagated under constraints so as to reach a stipulated final state. The dual-cone model is mathematically rich and offers a convenient way for expressing the essential aspects of a system's "intentions" as conative processes in the powerful languages of differential and integral geometry.

Imagine the aft cone as extending endlessly into the future and the fore cone as extending endlessly into the past. The total set of paths, in each extended open cone, represents the locus of all the solutions to a pair of independent one-point boundary problems—initial and final value problems, respectively. By contrast, their closed, diamond-shaped intersection represents the locus of the total set of path solutions for a single two-point boundary problem. The two points (initializing intention and finalizing goal) identify a tracery of paths in between as an omega cell. The space outside the omega cell is also meaningful for it holds all those paths that are not solutions to this two-point boundary problem, or, more precisely, the tracery of all paths emanating from the point of intention but never reaching the intended goal and likewise the tracery of all paths terminating in the final condition but not originating from the initial condition.

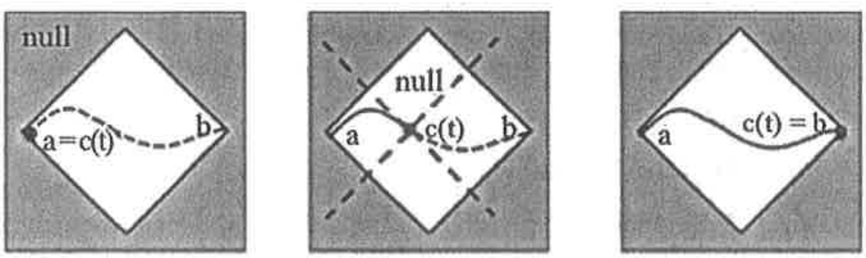

FIGURE 6 Omega cell (left-to-right): $a = c(t)$-to-b shows info for intended path at start (dashed curve); path a-to-$c(t)$ shows actor's control along path so far (solid curve); while $c(t)$-to-b specifies control still required. (color figure available online)

In sum, the beauty of this dual-cone model is that it combines under a single construct the solutions to a pair of one-point boundary problems while also excluding all paths that are not. This is tantamount to solving a two-point boundary problem that defines the tracery of all goal-paths belonging to the given omega cell. Also in need of solution is how to select from all the possible solution paths, bounded by the omega cell, that path, or a set of paths, that belong to the same tolerance set, that is, the set of those paths that, for all practical purposes, are the same. This is found in the notion of a *path corridor* (Mensky, 1993).

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Laws of Intentional Dynamics

The laws of thermodynamics apply to intentional dynamics in the following ways.

First law. A fundamental property of intentional dynamics is the conservation of *total generalized action*—an indicator of success the system has in staying on the intended goal-path (Shaw & Kinsella-Shaw, 1988).

Second law. Entropy production increases to the extent that action is less than goal-directed, say, because of control errors or information deficiency. Most generally, entropy production increases whenever a system loses its way so that work performed is less useful than it might be.

Third law. Entropy is higher in that region where action is undirected, which occurs just after the previous goal-path is completed and just before the next goal-path is initiated. During these pauses in directed action entropy increases because no useful work is being done.

Fourth law. In intentional thermodynamics the Fourth Law assumes the form of a mini-max principle (Figure 7). This means the effect of increased entropy production is a trade-off between overall global entropy and local path action optimality. Namely, as the optimality of path action increases (i.e., the goal-path control becomes more precise), the goal-path corridor narrows accordingly, thereby necessarily increasing the rate of entropy production (i.e., area outside the corridor grows). Thus global entropy production and local path action are dynamical complements.

HINT 7: MAKING EXTRINSIC CONSTRAINTS INTRINSIC

Differential equations, with extrinsic constraints (forcing functions and boundary

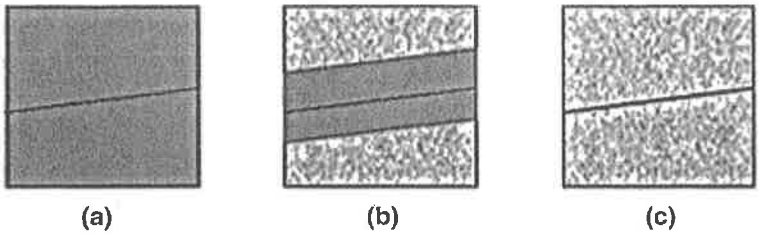

FIGURE 7 The Fourth Law is expressed by (a), (b), and (c) viewed left to right. As the path corridor narrows from maximum entropy and minimum optimality (a) to minimum entropy and maximum optimality (c), so the rate of overall entropy (area outside path corridor) increases.

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condition), are the standard mathematical tools for describing the causal dynamics of ordinary physical systems. But they are inappropriate for describing the intentional dynamics of physical intelligence. To be intentional, a system must have a degree of independence from extrinsic constraints if it is to be allowed free choice of its final state. Integral equations are appropriate because they have no need for such extrinsic constraints. Here techniques are presented for "absorbing" the forcing functions and boundary conditions of differential equations into the kernel of the transform of corresponding dual integral equations—a way of transforming differential descriptions into integral ones. The intertransformability of causal and intentional systems allows them to be directly compared. This suggests that a physical intelligence bridge might be built between the two—a step toward unification.

> ... from the physical standpoint a "boundary condition" is always a simplified description of an unknown mechanism which acts upon our system from the outside. A completely isolated system will not be subjected to any boundary conditions. (Lanczos, 1961, p. 504)

Absorbing the Forcing Function

Assume a system's performance of an action is partly dependent on an extrinsically controlled forcing function, $g(t)$. For the system (S) to perform the action autonomously, then the control of $g(t)$ must be "absorbed" into the system's control function. Let S take the form of the operator $\mathbf{L}[y]$, then the absorption process is shown by Equations 1–3:

$$\mathbf{L}[y] = \mathbf{P}(t)\ddot{y} + q(t)y + r(t)y = g(t). \tag{1}$$

Solution y for this system depends on the forcing term $g(t)$. The linear operator $\mathbf{L}$ on the left-hand side of Equation 1 can be used to represent the ordinary differential equation (ODE) on the right-hand side. Using the operator notation, one can translate the ODE problem into another problem defined in Hilbert space. Finding a solution for our differential equations becomes a problem of finding functions in the Hilbert space of double differentiable functions that allow $g(t)$ to be replaced in **L** (i.e., S's formal representation).

The mathematical techniques used to transfer the $g(t)$ control to **L** involves the well-known fact that nonhomogeneous second order ODE (SODE) with homogeneous boundary conditions can always be put into a homogeneous form with inhomogeneous boundary conditions. This is accomplished by reformulating the boundary conditions (outside constraints from the environment, E) that the equation must satisfy if it is to "absorb" the forcing function. Formally, this requires the knowledge of a particular solution to Equation 1. The well-known mathematical theorem says that with the help of a particular solution, the task of finding any other solution is reducible to the task of finding solutions of the homogeneous equation

$$\mathbf{L}[y] = p(t)\ddot{y} + q(t)\dot{y} + r(t) = 0. \tag{2}$$

The general solution of Equation 1 can be expressed with the linear combination of any two independent solutions of Equation 2 and a particular solution of Equation 1, as shown in Equation 3.

$$y(t) = y_p(t) + c_1 y_1(t) + c_2 y_2(t). \tag{3}$$

One may translate this formal decomposition of solutions into the language of intentional dynamics. Finding a particular solution means proving the viability of the required action control (controllability) that held for the E system (as a self-adjoint system) and remains invariant when passed to S. Metaphorically, S has successfully searched the functional space of solutions to the homogeneous equation.

Getting rid of the forcing function as an extrinsic influence accomplishes the first step in intentionalizing a dynamical system. But boundary conditions are also extrinsic constraints on a system that need to be rendered intrinsic. This problem is addressed next.

Absorbing Boundary Conditions: The Sturm-Liouville Theory

Two important points need to be noted about natural boundary conditions and the relationship they have to differential equations used to capture the laws of nature.

First, a differential equation alone, without boundary conditions, cannot provide a unique solution. But boundary conditions (e.g., goal-constraints) are not

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part of the law that might be expressed in differential terms. Rather, they are logically complementary to the law and must be added as extrinsically imposed constraints on the system. From the physical standpoint a "boundary condition" is always a simplified description of an unknown mechanism that acts upon a system from the outside. A truly intentional system will not be subjected to any boundary conditions (as shown later).

Second, for S to avoid information-specified hard E constraints, it must assimilate those constraints as changes to the intrinsic control parameters of its intentional dynamics. That is, it must somehow "absorb" constraint information into its dynamical equation. This cannot happen in the case of differential equations, but it can if the differential equations were transformed into a corresponding (dual) integral equation. An equation of the latter kind has no boundary conditions aside from the limits placed on it. This transformation process can be accomplished as follows:

Equation 2 is said to be exact if it can be written in the form

$$d[p(t)\dot{y}]/dt + f(t)y = 0, \tag{4}$$

where $f(t)$ is expressed in terms of $p(t)$, $q(t)$, and $r(t)$. By equating the coefficients of the aforementioned equations, and then eliminating $f(t)$, one finds that a sufficient and necessary condition for exactness is

$$\ddot{p}(t) - \dot{q}(t) + r(t) = 0. \tag{5}$$

If a linear homogeneous SODE is not exact, then it can be made so by multiplying it by an appropriate integrating factor $s(t)$. For this, one needs $s(t)$ such that

$$s(t)p(t)\ddot{y} + s(t)q(t)\dot{y} + s(t)r(t)y = 0, \tag{6}$$

which can be written as

$$d[s(t)p(t)\dot{y}]/dt + f(t)y = 0. \tag{7}$$

Again, by equating coefficients in these two equations and then eliminating $f(t)$, one discovers that the function s must satisfy

$$p\ddot{s} + (2\dot{p} - q)\dot{s} + (\ddot{p} - \dot{q} + r)s = 0. \tag{8}$$

This is the adjoint equation to the original Equation 2.

For a large class of physically meaningful equations, it can be shown that the original equation (the primal) has an adjoint (its dual) whose adjoint is the original equation (double dual). This is called a *self-adjoint* equation. The

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original equation stated earlier is a case in point. It can be shown that the condition for Equation 2 to be self-adjoint is that

$$\dot{p}(t) = q(t). \tag{9}$$

A very useful fact is that any SODE can be made self-adjoint by multiplying from the left by

$$\int \frac{q(t) - \dot{p}(t)}{p(t)} \tag{10}$$

Because the concept of Hilbert space and the **L** linear operator on it has been introduced, one can talk about eigenvalues and eigenvectors (eigenfunctions) of this operator. Given this theoretical framework, it is natural to seek a solution of $\mathbf{L}[y] = g$ by looking for $\mathbf{L}^{-1}$, the inverse operator of **L**. In many important cases, it can be found. The inverse operator is an integral operator in the form

$$\mathbf{L}^{-1}[g(t)] = \int_a^b G(t, v) g(v) dv. \tag{11}$$

The G kernel is called the Green's function—the propagator of the path of operator **L**.

The first charge is to guarantee the existence of the Green's function. The general condition for its existence is that the homogeneous equation with the given boundary conditions must have no solutions that are nondegenerative. Generally, finding the Green's function is not a simple problem. For a Sturm-Liouville system, however,

$$d[p(t)y] + f(v)y = g \tag{12}$$

is a Green's function that can always be found by means of the following theorem. Suppose that the system given by Equation 12 has no null eigenvalues (i.e., has only a nondegenerative eigenfunction) on the interval $[a, b]$, and assume the imposed boundary conditions are

$$cu(a) + du'(a) = 0 \tag{13}$$

$$eu(b) + du'(b) = 0, \tag{14}$$

where $p(t) > 0$, $dp(t)/dt$ exists and is continuous in $[a, b]$, and $f(t)$ is continuous in $[a, b]$ where $\{f(t) \in C[a, b]\}$, c, d, e, and f are nonzero. Then, for any $f(t) \in C[a, b]$, the system has a unique solution,

$$u(t') = \int_a^b G(t', t) g(t) dt, \tag{15}$$

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where $G(t', t)$ is the desired Green's function given by

$$G(t', t) = \frac{u_2(t')u_2(t)}{p(t)W(t)}, \quad \text{for } a < t < t',$$

$$G(t', t) = \frac{u_2(t')u_2(t)}{p(t)W(t)}, \quad \text{for } t' < t < b,$$

where the $u_i(t')$ functions are nonzero solutions to the homogeneous system given by Equation 12, with the boundary conditions specified by Equations 13 and 14, and where $W(t)$ is the Wronskian. It should be noticed that the given boundary conditions, as extrinsically imposed requirements on the ODE representation of the system represented by Equation 12, are now absorbed into the integro-differential equation (IDE) representation given by Equation 15. Now all extrinsic constraints (forcing function and boundary conditions defined on E) *have been rendered intrinsic* to the system S. (For a more detailed exposition, please see Shaw, Kadar, Sim, & Repperger, 1992.)

An Intuitive Example

The main point of this mathematical argument can be illustrated intuitively. A blind person can learn to move though a cluttered environment without collisions by acquiring a "cognitive map"—and thus ridding herself or himself of dependence on extrinsically imposed local constraints. No longer is there a need to bump into the obstacles to be informed of their presence and location. The concept of a *cognitive map* is just an intuitive term, an alternative statement, that refers to the result of the process that renders constraints intrinsic, with respect to system S, that were formerly extrinsic constraints imposed on system S by environment E. Similarly, when a novice becomes an expert, her actions acquire a fluidity that the inexpert lacks. She seems to function more globally as a "free" path propagator—a Green's function, if you will—without need for frequent pauses to make overt choices of control acts that depend on local constraints.

The preceding invites the following question by way of summary: Can this adjoint information-control formalism (allowing modeling of the perceiving–acting cycle) be generalized to incorporate all constructs of intentional dynamics, for example, omega cells, choice-points, and goal-paths?

HINT 8: SINGULARITIES, DUALITIES, AND ANALOGIES IN INTENTIONAL THERMODYNAMICS

If intelligence is truly physical (i.e., thermodynamical) rather than just biological, then it must fit consistently into the law structure of physical cosmology. Unfortunately, in doing so it must also contend with certain fundamental cosmological puzzles, the nonintegrable "singularities," just as any other physical hypothesis must. The quest for intelligence from first principles might benefit from a brief review of these troublesome phenomena.

The Challenge of Singularities

In mathematics, a singularity is a nonintegrable, infinitely differentiable point. It is a point at which a function takes an infinite initial (or final value), as is the case with poles of a field (e.g., sources and sinks). For example, on the real number line the function $f(x) = 1/x$ has a $\pm\infty$ singularity at $x = 0$. In the physics of space–time, matter/energy is infinitely dense at the center of a black hole or at the initial point of the Big Bang. A singularity can have *local* or *global* influence. For instance, a black hole is a local singularity in space–time, whereas the Big Bang, as the unique source of everything, is a global singularity from which everything (including space–time) unfolds.

Likewise, intentional dynamics depends on both global and local singularities. Every intentional action begins with a pair of global singularities—*a goal* from which information emanates and toward which actions are directed, and a *perspectival point* at which goal-specific information is detected and from which goal-directed actions are initiated. Unless the action is under ballistic control, and thus on a least action path, local singularities will likely be encountered along the way—such as *choice-points* at which the goal-path must branch to avoid thwarts if it is to proceed. (See concept of omega cell in Hint 6.) Over its lifetime, an intentional system cycles repeatedly over intention-to-goal (i.e., over successive omega cells). This is geometrically similar to the new cyclical theory of cosmological evolution (Steinhardt & Turok, 2006). Here, the cosmos cycles, repeatedly and endlessly, from initial Big Bang to final Big Crunch. Admittedly, the analogy may seem strained—but it will seem much less so if additional points of similarity can be found.

Analogous Event Horizons

Global and local singularities inter alia share a key structural characteristic—an *event horizon*. A black hole's event horizon marks the boundary from which no light or heat can, in principle, escape from the gravitational hold of the local singularity. By contrast, the cosmic singularity's event horizon marks the boundary at which its expansion is accelerating so fast that light cannot reach an observer in its wake. Consequently, even the most powerful telescope cannot in principle penetrate far enough into the remote past to reveal the universe's origin or even the spreading edge of its expansion. Also, within either horizon, a process smoothes

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out all inhomogeneities, anisotropies, and curvatures. This is very important in explaining the properties of the universe we observe (Steinhardt & Turok, 2006).

Event horizons also surround systems that exhibit intentional dynamics. The inner workings that determine goal selection (operationally, an intention) and the manner of approaching the goal (goal-path) are hidden from outside observation (philosophers call this the "problem of other minds"). Yet the system can readily detect information from the outside just as a black hole is responsive to the matter or energy that impinges upon it. Although imperfect, the analogy between cosmic singularities and singularities of intentional dynamical systems is nevertheless intriguing.

In what follows, we explore further the analogy between cosmic singularities and the singularities of intentional dynamics, which, by our assumption, must also underwrite intelligence from first principles.

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Black Hole Laws and Thermodynamic Laws are Duals

One of the most important findings of the last century was the discovery that the laws of black hole mechanics are not just analogous to the laws of thermodynamics but *are* the thermodynamic laws *in disguise* (Thorne, 1994). Strictly speaking, they are not identical but are isomorphic duals—as in the case of projective geometry where theorems remain valid even when the point and line terms are interchanged. Similarly, each black hole law (theorem) is dual to a thermodynamic law (theorem) if one only replaces the phrase "horizon area" with "entropy" and the phrase "horizon surface gravity" with "temperature." There is an interesting backstory to this important finding.

In the 1970s the leading experts (Hawking, Penrose, Wheeler, et al.) believed that because a black hole singularity was simplicity incarnate, it had no room for randomness and thus was the opposite of entropy. A graduate student, Jakob Bekenstein, strongly disagreed because he saw that if this were so, it would violate the Second Law (Thorne, 1994). He reasoned that if black holes had vanishing entropy, then any objects that fell into one would carry their entropy with them and thereby reduce the universe's overall entropy. This of course violates the Second Law, which dictates that entropy in the universe should never decrease. To agree with the Second Law, a black hole must have entropy that can increase when something falls into it. Thus Bekenstein rightly concluded that its horizon's surface area must increase proportionally. Finally, after much debate and calculation, the field came to agree that Bekenstein had to be right.

White Hole Dynamics as Dual of Black Hole Dynamics

A white hole is the dual of a black hole. As originally predicted by general relativity, a white hole horizon is a boundary of space–time that, ideally, allows

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no entry from the outside but from which heat, light, and matter may escape. Likewise, as predicted by general relativity, a black hole horizon, ideally, can be entered from the outside but allows nothing to escape.

Later, it was shown that the horizon around either a white hole or black hole is not really a perfect one-way impermeable "membrane." Some heat is able to radiate from the inside of a black hole's horizon, and, conversely, pass into the white hole from the outside—in this way they are each able to attain thermal equilibrium. According to Stephen Hawking, black holes and white holes are duals in the sense that where the former is an absorber (sink) of matter and energy, the latter is an emitter (source; Thorne, 1994).

In intentional dynamics we have a similar duality: an intentional system is in dynamical equilibrium when sufficient information is emitted to specify a goal-path while, dually, evoking a system's prospective control needed to follow the goal-path. This means that a system following a goal-path is guided by a variational (optimal) solution, as if sensitive to the least action path. In doing so, it is curious but true by definition, as described by the mathematics, that the system *does no work to stay on a goal-path geodesic.*

It is tempting to see analogies between the black hole–white hole mechanics and the ecomechanics of intentional systems. Consider this: *Goal (source) emits information (like a white hole)* and its dual *system (sink) absorbs information (like a black hole).* But unlike the cosmic case, an ecosystem has additional dual perspectives from its agent and its environment components, respectively, of the following form: *System (as an actor) "emits" goal-relevant control (like a white hole)* and its dual the *goal (as an attractor) "absorbs" the system's goal-directed control (like a black hole).* Because an intentional dynamical system has a pair of duals, where an ordinary dynamical system has but one, the former system has more degrees of freedom than the latter and thus more latitude for engendering the complexity normally attributed to intelligent systems.

An interesting implication of the foregoing is that a first principle in the quest for "intelligence from first principles" is *dual alternative descriptions* (i.e., the system and environment's reciprocal perspectives). Such are foundational to ecophysics but not ordinary physics.

HINT 9: COSMIC SELF-TUNING THROUGH CYCLES OF IMPREDICATIVE LOOPS

The logical structure of the four thermodynamic laws may help reveal their essential role in cosmology. And because intentional dynamics has a thermodynamical interpretation (as shown in Hint 6), it, too, would fit into physical cosmology. In this way intelligence construed as intentional thermodynamics

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would be truly abiotic, existing (as it were) from the very beginning of all things physical.

The Origin of Singularities

Proponents of the anthropic principle maintain that for the cosmos to have the properties observed today (e.g., intelligent systems), the Big Bang's initial conditions must have been very finely tuned (Barrow & Tipler, 1988). But attuned how? Perhaps, an impredicative loop of laws (see examples in Chemero, this issue) might account for this self-tuning. It is a prospect worth considering.

More specifically, during the epoch of inflation, the origin of the four laws of thermodynamics may have provided the means for this self-attunement. Inflation theory may explain how the visible structures in today's universe were created. One reasonable hypothesis is that the start-up of the universe was due to spontaneous *quantum fluctuations* allowed by Heisenberg's uncertainty principle. The virtual particles created by these fluctuations at the Planck (10^{-35} meters) scale (the so-called false vacuum) produced perturbations in microscopic space–time regions. After their gravitational collapse, the perturbations were magnified during inflation to cosmic size. These upscaled perturbations acted as "seeds" for the formation of stars and galaxies from which all else followed.

The Standard Theory postulates the Big Bang singularity as a way to get the creative evolutionary process under way. Among the things presumed to emerge were local singularities, or black holes. The study of these singularities suggests a key role that thermodynamics must have played at the start of cosmic evolution. Our interest is whether that key role included originating intelligence. Here is one argument in favor of this idea.

Motivating the Global Singularity Postulate

Why postulate something as troublesome as the Big Bang singularity? Here are four lawful reasons.

First Law: For the *conservation law* to apply there must be a source of energy to conserve; hence the singularity is postulated to be that source.

Second Law: For the *entropic law* to apply the singularity must have had some entropy, albeit very low (see Lineweaver, 2010), otherwise the Second Law would have nothing to increase.

Fourth Law: For the *maximum entropy production law* to apply the Second Law must ensure a nonnegligible rate of entropy flow from the singular source, otherwise the Fourth Law would have nothing to expedite.

So far, the roles of three of the four laws in motivating the singularity postulate have been revealed. It remains to reveal the remaining law.

Third Law: The *zero-point law* plays a role of central importance to the other three laws. Whereas they provide strong *logical* reasons for postulating the singularity, the Third Law is postulated to explain its *physical* origin—something none of the other laws can do. How it does so needs some background. The zero-point energy law does not really belong to thermodynamics but its necessity justifies borrowing it from quantum field theory, as explained next.

A New Zero-Point Energy Law

There are two versions of this law to consider. In traditional thermodynamics the old version of the Third Law states that the entropy of space–time, like a perfect (hyper)crystal, approaches zero as the absolute temperature approaches zero. Thus this law provides the much needed absolute zero reference point for the determination of entropy. The entropy determined relative to this point is the *absolute entropy*. But this old version of the Third Law, unlike the other three, is not fundamental but is derivative of the statistical definition of entropy. This will not do, for if we are to have a principled basis for physical intelligence, it is laws rather than chance that must underpin physical intelligence. For this purpose we need, instead, a new version of the Third Law that makes its fiduciary role as fundamental as the other three laws. Quantum field theory provides the version needed.

Under quantum field theory the old notion of a void, or empty vacuum state, is replaced by the exotic notion of the *false vacuum*. Simply put, the false vacuum is a local minimum, but not the lowest energy state, and somewhat like a first-order phase transition in being metastable (e.g., melting ice or boiling water). This means if you could subtract maximum energy from any system, surprisingly, the ground level reached is *never zero* (i.e., an empty vacuum), as the old version of the Third Law predicts. Rather, because of quantum fluctuations, excess positive and negative energy is continually being produced (analogous to the Casimir effect) in the form of short-lived virtual particles. The uncertainty principle guarantees that the ±charged virtual particles produced at this Planckian scale (10^{-35} m.) over time always maintain a zero-point balance (often called the "false" vacuum). Thus the First Law is never abrogated. However, because not all particles emerge from the quantum soup *at the same time*, the new Third Law permits production of some negentropy to be amplified during inflation.

As explained earlier, this spontaneous production of order from "nothing" by quantum fluctuations is responsible for the universe as we know it. Hence where the Third Law creates the order ex nihilo, helped along by inflation, the other three laws work together to sustain the order created. As we see later, this interdependence of the four laws is tantamount to their forming a synergy—a systemic manifestation of an impredicative loop (Turvey, 2007).

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This order creation process has been continuously at work since the Big Bang. It also controls the cosmological constant (a fudge factor postulated by Einstein) that determines whether the universe expands, is steady-state, or contracts. Today, it is thought by some to be synonymous with the process that produces the dark energy that repels while gravity attracts (Penrose, 2005). Depending on the ratio of gravitational energy to dark energy, the universe might in this way swing eternally between cycles of Big Bangs and Big Crunches, as the cyclic cosmologists hypothesize (Steinhardt & Turok, 2006). Just a hypothsis but interesting nevertheless.

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An Impredicative Sorites

An important point of logic should be noted here. The aforementioned argument from the interdependence of the four laws takes the logical form of a *sorites*—a chain of syllogisms such that if you take one to be true, then you must take them all to be true. The chain of syllogisms obeys a kind of logical domino principle (a sequence of *modus ponens—affirming the antecedent*) where one domino falling causes them all to fall. Consider the sorites of the aforementioned law entailment structure (read '→' as *entails*):

singularity → first law → second law → fourth law → third law → singularity

This sorites of logically interdependent laws also exhibits the "vicious circle" principle or *impredicativity* property, namely, *singularity* ⇔ *laws* (read '⇔' as *if and only if*), the impredicativity exists because the laws and singularity coimplicate one another as in the chicken-or-egg conundrum. One needs the laws to account for the singularity and the singularity to account for the laws—a vicious circle. Or, perhaps, not so "vicious" if it provides the means for a system to tune and retune its own recurrent initial conditions. The foregoing invites speculative questions of this kind: Will a deeper study of impredicative loops reveal more clearly how the Fourth Law effects a system's "self-attunement"? Could it be likened to a nonlinear *super-heterodyning* circuit that optimizes the quality of a signal by creating negentropy not originally present?

HINT 10: PHYSICAL INTELLIGENCE AS A THERMODYNAMICAL ATAVISM

Because intentional dynamics has a thermodynamical interpretation (as shown in Hint 6), then like all other thermodynamic phenomena, it should have a natural place in physical cosmology. But did it originate, along with the thermodynamical laws, soon after the Big Bang, or did physical intelligence emerge much later during some special epoch? The possibility is entertained that physical intelligence was distributed throughout the warp and woof of the cosmos by the Big Bang, and being synonymous with intentional thermodynamics, it would be truly abiotic—existing, as it were, from the very beginning of all things physical.

Atavism

If intelligence were a characteristic of the physical world before life emerged, then today's intelligent life forms would be continuous with the initial conditions of the Big Bang singularity that held the seeds for intelligence. If so, then intelligence would be an *atavism*—that is, a characteristic that persists from the earliest time. No epoch thereafter would be any more special than another, and the claim that intelligence is unique to the biological era would lack foundation.

Also, if we could look backward through cosmic history, psychology would be seen to shade off into physics and psychological intelligence would blend with physical intelligence, thereby voiding the historically popular but fruitless postulate of mind–matter dualism. For historical reasons, this possible philosophical consequence of a successful program seeking intelligence from first principles deserves some serious thought. Contemporary science routinely treats the dichotomy of mind and matter as a consensus "fact" rather than an unproven hypothesis. The dichotomy is so ill defined that its status is less that of scientific hypothesis and more that of speculative metaphysical conjecture. So it seems that considerable time and resources might have been and are still being uselessly squandered.

During evolution, the essentials of physical intelligence would have persisted as invariants under the action of the First Law. This is a necessary condition. But if, as commonly assumed, intelligence generally increases over evolution, then the action of the Second Law to increase entropy must do so in a way not to stymie the growth of intelligence. This, too, is a necessary condition. Not to stymie the unfolding of intelligence from first principles, however, is too weak a condition; something more is needed to supply the sufficient condition for its putative increase. This of course is the job of the Fourth Law, as previously argued (Kondepudi, this issue; Swenson & Turvey, 1991).

The Fourth Law dictates that the system realizing the most work from its energy, before returning its leavings (as it must) to the environment, is not only the most efficient energy utilizer but is also the most efficient entropy producer. Thus, the more efficient a system is, the greater its entropy contribution to the universe. This is true of all reproducible systems (e.g., stars, living systems, economies).

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What Is the Causal Status of the Fourth Law?

With all the industrialized means human intelligence has created, it seems its evolution provided a better way to exploit physical intelligence and thus make the Fourth Law more efficient than it would have been otherwise. Intelligent actions promote maximum entropy production regardless of the embodiment of the synergy responsible—whether physical or biological. Through what process did human intelligence arrive on the scene? Perhaps biological support for intelligent actions emerged when physical systems underwent some kind of phase transition brought on by a "collective instability" of the evolutionary process (Laughlin, 2005).

One wonders if the presence in evolution of such collective instabilities that amplify entropy could be *due to* the Fourth Law? Or, are they what we *mean* by the Fourth Law? The hallowed status of laws in science makes it easy to get this the wrong way around. We must remind ourselves that laws, like symmetries, are empirical discoveries. They are more than inventions by human intellect but less than intrinsic causal agency lodged in the universe. One view that seems right to us is that laws summarize but do not explain the processes from which they are abstracted; rather, the laws are explained by the processes (Feynman, 1967). Consequently, the Fourth Law describes an important aspect of the universe, namely, a tendency toward maximum entropy production, but does not make it so, no more than the law of gravity makes things fall toward the center of the earth. Instead, it was from the observations that things fall in this manner that allowed the law to be formulated. In short, the origin of the Fourth Law is as big a mystery as the origin of the law of inertia. We may use it to describe but should attribute no causal efficacy to it.

Intentional Thermodynamics Redux

An important claim is that the laws of intentional dynamics and the laws of thermodynamics, like black hole laws and thermodynamic laws, are also dual isomorphs. (See Hint 8 for details.) This claim sat behind the chief ideas promoted in Hint 6 regarding intentional *thermo*dynamics. There we argued that the laws of black hole dynamics are dual to both thermodynamic laws and intentional dynamic laws. Specifically, choice-point singularities the system must pass through function alternately like black/white holes—black hole sinks on entry and white hole sources on exit—whereas the intent-point that initiates goal-paths functions like a Big Bang singularity (source) and the goal-point that terminates goal-paths like a Big Crunch singularity (sink).

Still to be shown, however, is exactly how the logical structure of the laws of intentional dynamics motivate the start singularity (goal-selection) for the unfolding of an intended action—just as the logical structure of the laws of thermodynamics was shown to motivate the start singularity for the unfolding of the universe.

Hence we see intentional dynamics must also contend with both local and global singularities. These singularities also have event horizons that collectively form an *omega cell* (where horizons are functional boundaries, like membranes, that allow something, such as heat, only one-way passage; Thorne, MacDonald, & Price, 1986). Whereas the black hole's horizon is due to gravitational attraction of its singularity, and the Big Bang's horizon is due to the superluminal acceleration of expansion from its singularity, so the omega cell's horizon is due to the maximum rates at which action paths can be produced to reach its singularity—the goal (Hint 6). Thus whatever role thermodynamic laws play with respect to the other singularities, so must they with respect to intentional dynamics.

That intentional dynamics is a form of thermodynamics gains further support from the fact that it is all about positive and negative entropy. Positive entropy is a product of the Second Law whereby energy once available for useful work is no longer available. Thus all paths that originate from the same initial intent-point but fail to reach the final goal-point contribute to total positive entropy. Conversely, negative entropy is a product of the Fourth Law whereby energy once *un*available for useful work now becomes available. Here all paths that originate from the same initial condition and succeed in reaching the intended final condition (or goal-point) contribute to total negative entropy. Applying more energy efficiently to do useful work entails that the entropy eventually produced is greater than that produced by the energy wasted on useless work. It seems, then, useful work is an agent of the Fourth Law, having as it does a greater potential for entropy production than useless work.

Similar reasoning suggests the Big Bang was the largest potential for entropy because it produced much useful work that went into the formation and evolution of galaxies, planetary systems, and, eventually, of living species and the ever more efficient factory processes they create year after year. Put concisely, intentional thermodynamics is simply the Fourth Law incarnate. Thus physical intelligence being wedded to thermodynamics must also have originated in the earliest stages of cosmic evolution rather than some more recent epoch. Admittedly, the arguments presented here and in the previous sections are conjectures. But it is prudent and heartening to recognize that though *all models are wrong some are nevertheless useful* (Box, 1979).

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