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Intentional Dynamics of Situated Action

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Abstract. A novel approach to goal-directed behavior is developed by situating the perceptual control of action in a four dimensional Minkowski space-time. This intentional dynamics exhibits all the lawful chracteristics of simple purposive acts but without recourse to mental constructs, wherein no clear systematic account has heretofore been given to the requsite cooperation of information and control. Although the mathematical support for this approach is discussed at only an intuitive level, the basis for a more rigorous analysis is made apprarent though minimal modifications to diagramatic techniques borrowed from Einstein's special theory of relativity.

1 Introduction: The Goalpath Navigation Problem

For ecological psychology it has been suggested that the perceiving-acting cycle should be the smallest unit of analysis. We would like to amend this suggestion. It now seems to us that the smallest unit of analysis must be *the perceiving-acting cycle situated in an intentional context*. What this means is the main topic of this paper.

To situate the perceiving-acting cycle under intentional constraints is to identify a space-time context in which the actor selects a goal, and then selects from all causally possible paths those that are potential goalpaths, and from these the actual goalpath to follow. The generic problem, therefore, is how best to describe *the action* of an organism. A successful *action* (henceforth defined as *a goal-directed behavior*) minimally entails selecting a (distal) target and moving over a space-time path in an intended manner to that target. This implies that the distal target and the future goal-state of the actor must make their presence felt in the information and control accompanying its current state. Thus somehow the distal must logically condition the proximal, so that the actor's changing relationship to the intended final condition acts to re-initialize (update) the actor's current condition. This is what it means for a space-time path to be *a goalpath*.

A careful consideration of these requirements suggests that *a field of control-specific information* must exist in which the actor and the intended goal both participate. Furthermore, this field of control-specific information must at the same time and in the same place be *a field of goal-relevant control.* Hence each space-time locale in the field is characterized by both an information value and a control value. Such values that go together in this dual fashion are said to be *conjugate information-control values*. The relationship between the energy controlled and the information detected with respect to the goal is said to be *adjoint* by nature—something all creatures are born into because of evolutionary design. When this adjoint relationship, however, leads to successful goal-directed behavior (something that often has to be learned), then the adjoint relation of information to control is said to have become *self-adjoint*.

One recognizes in this problem of goal-directedness the need for what the Würtzburger ('imageless thought') School of psychology called a 'determining or organizing tendency' (Einstellung). We call this Einstellung, when augmented with a boundary condition, *an intention* because it is the goal-sensitive, agentive function (a *cognitive operator*, if you will) which determines goal-selection and organizes the dynamics under a 'control law' designed to serve the intention.

The existence of such a field of conjugate values, in which information and control might become self-adjoint, would explain how everywhere that the animal might venture there are opportunities for acting toward the goal in an intended manner (excluding, of course, those places and times where the target is occluded or barriers block its accessibility). *We shall show that such an information-control field has a natural interpretation in an adjoint information/control theoretic formulation of Minkowski space-time—the event and worldline geometry of Einstein's special relativity.*

As a step toward this field theoretic model, we postulate an *intentional process* which acts (as an Einstellung) to set up a perceiving-acting cycle (along the lines discussed by Shaw & Kinsella-Shaw [1]). The actions that the perceiving-acting cycle *might generate* over space-time define the causally possible family of goalpaths. Here intention, defined as a cognitive operator, tunes the perceiving-acting cycle by directing both the attention and the behavior of the actor toward the goal. A coherent account of this intention-driven dynamics would remove the mystery of how actors maintain informational contact with their goalpaths; namely, they do so by direct perception when the goal is detectable, or otherwise, when not detectable (say, over the horizon), they must navigate either by *indirect perception* or by direct perception *plus dead reckoning*. For humans, indirect perception may be achieved, as James J. Gibson [2], the founder of ecological psychology, suggests, by means of verbal instructions, or by use of a map (with target coordinates specified), perhaps, drawn or remembered. As nautical navigators discovered, however, a map alone is not adequate; one also needs a compass to determine directions at choice-points, and a chronometer to satisfy a schedule of departure and arrival times if contact with the goalpath course is to be maintained.

Hence the approach proposed in this paper can be summarized as *a field of conjugate information-control values, with paths being generated by a perceiving-acting cycle which is motivated and guided by intention as a field process.* This account contrasts sharply with more traditional accounts. Let’s consider the contrast:

Since animals presumably do not use navigation tools, then they (like humans without benefit of maps, compass, and clocks) must rely on direct perception *plus dead reckoning* to perform the same navigation functions. Traditional psychology assumes, not unreasonably, that under such circumstances they direct themselves by 'cognitive maps' (where intended goals are somehow attentionally distinguished from non-goals). The evidence for the existence of cognitive maps, one might argue, is the actor exhibiting a 'sense of direction' at choice-points, and a 'sense of timing' which keeps the actor on schedule in arriving at and departing from sub-goals. Here the cognitive modeling strategy proceeds by positing internal mechanisms that internalize the map, compass, and chronometer functions. Regardless of either the truth or usefulness of such internal constructs, the success of the internal state modeling strategy is predicated on a successful actor having access to goal-specific information and goal-relevant control along the goalpath. The field notion also putatively captures the sense of the *social invariance* of the information and control opportunities which

(a) allows an observer to see which goal an organism is most likely pursuing, and

(b) allows different organisms to compete for the same goal.

Hence one may debate whether the field of information and control manifests itself *internally* (as cognitive psychologists maintain), *externally* (as behaviorists have maintained), or *dually* (as we ecological psychologists propose), but the field's existence is without question, being assumed by all parties alike. [3]

Regardless of whether navigation is achieved by direct or indirect perception, the actor's control process must maintain invariant contact with the intended goal over some dynamically developing course of action—a potential goalpath. Consequently, a theory is needed for what constitutes goalpaths, and how they are recognized, selected, and followed. We assume that a goalpath is *generated*, as a segment of a worldline in space-time, by the actions of the perceiving-acting cycle engaged by the organism. Before considering the details of how this engagement is to be formally characterized, we consider the general intuitions that underwrite the intentional dynamics approach to this problem.

2 Modeling Systems that Exhibit Intentional Dynamics

Historical Aside: I met James Gibson at the University of Minnesota in the summer of 1968 where he presented a seminar on his theory of direct perception. I was a young faculty member at the time. During that summer I was fortunate to have this opportunity to interact with him both inside and outside the seminar. Soon after this, Gibson invited me to come to Cornell for the 1969-1970 academic year to participate in his ongoing perception seminar. There he presented us with the problem of finding a formal characterization for his novel idea of perception as direct rather than mediated. After hearing me present the idea that the duality concept seemed a possible means for representing "directness," he agreed that this seemed reasonable and was worth pursuing—but, he admonished me, to be very careful in developing this idea. In the ensuing decades I have tried to do so [4].

Intentional dynamics *inter alia* faces two problems:

First, how is the perceiving-acting cycle comprising a dual relationship between information and control to be formally described? A decade ago, we proposed an answer from the perspective of a variant on optimal control theory called *adjoint systems theory* [5].

Second, how is the field of conjugate information and control values available to the perceiving-acting cycle to be made formally explicit? Here we borrow from a novel version of quantum theory the image of a particle carrying out continuous measurements (i.e., information detection) as it moves through a field toward an attractor [6].

The goal, ultimately, is to provide the generic mathematical description of an organism with a complex interior, being driven by internally produced forces and guided by externally available information onto a goalpath toward a future goal-state. This image of a complex animate 'particle' exhibiting intentional dynamics in a field of information and control replaces the standard (Hamiltonian) image of a particle with a simple interior, being driven by outside forces onto a 'least action' path that is indifferent to any future goal state.

Given an actor at some space-time location who intends to connect with an accessible target at some other space-time location, then there will exist a family of causally possible goal-paths. This set is bounded in space-time by the maximum rates of causal action allowed by the (e.g., locomotory) capabilities of the agent who intends the goal. For convenience, we call such a bounded region of goalpath possibilities, an *Ω-(omega) cell* —a construct of *ecological physics* which falls between the cosmological scale and the quantum scale [1] [5] [6]. At each moment, along each path there is a certain amount of energy the agent must control if the action is to be in the goal's direction. The amount of control is perceptually specified at each of these points on each goalpath by goal-specific information. What form does this specification take?

This question poses, in part, a version of the so-called 'inverse dynamics' problem for psychology [7] whose solution has been discussed elsewhere (see [8]; [9]). But since the agent could be on any one of a number of paths, then some perspectivally weighted information and control quantity must be available at each point on each possible path. Quantum physics offers us a lesson on how to do such weighting.

Elsewhere [3], I have shown how, even in classical physics, a single quantity exists as *an inner (scalar) product* of information and control which is defined at each point along the goalpath. We offer the following intuition as to what this means: From the internal frame of the actor, one might think of the control-specific information as a wave crest that accompanies the moving agent at each point along the goalpath—from initial to final condition. Let's call this an 'information wave' since it embodies all the dynamical knowledge about the goal (namely, where it is and how to get there) available to the actor as an acting perceiver.

Alternatively, from an external frame of a scientific spectator, one might think of the 'information wave', as it moves over the distribution of possible paths, as specifying at each point, on each path, the likelihood that a perceiving-actor, who intends the goal, will be found there. *Hence intentional dynamics assumes that well-intentioned, normally competent actors will tend to go where goal-specific information is most likely to be found and goal-directed control is most likely to be achievable*.

Our aim is to show that the existence of such an 'information wave' is by no means fanciful under the conception of intentional dynamics, as developed by us in earlier papers—although such a dynamical construct as a 'information wave' has not before been introduced. Consequently, all the mathematics that follow are designed to explicate this intuitive interpretation. Consider the proposition that *when the 'information wave' embodies information and control that are only adjoint with respect to the goal, then the actions taken can at most be relevant but unsuccessful. However, when they are self-adjoint, then the actions are, by definition, both relevant and successful.*

Although this is not the place for mathematically developing this new explanatory construct, instead, let's consider the current status of the theory of intentional dynamics that has emerged over the past fifteen years or so. The purpose of the next section is twofold: To clarify what one might mean by the claim that *actions must be situated in an intentional context* and to give an overview of the problems that a theory of the intentional dynamics of such situated actions must face. We also indicate the extensions to the theory proposed by the current effort.

3 Intentional Dynamics: An Overview

In earlier work we proposed representing the perceiving-acting cycle of an actor as a continuous (Lie) group of complex involutions. This approach draws its inspiration and borrows its mathematical techniques from classical mechanics (e.g., [10]). The virtue of the continuous group representation is that it allows one to characterize the 'intentional' action of systems as the 'flow dynamics' of a *generalized Hamiltonian* action potential which follows paths dictated by a 'least action' principle. We have called this generalized approach *intentional dynamics* and attempted to clarify the notion of the new action potential as follows [7]:

> For a flow to exist [over a goalpath], there must be a force. A *force* can be defined as *the gradient of some potential*. In some sense a goal can be said to exert an *attractive force* on the system. The sense we suggest is as *some kind of* potential difference between the endpoints of a goal-path. For this to be more than mere metaphor, we must find some way of allowing the interior gradient of the organism's metabolic potential to interact with the exterior force field of the environment. This can only take place through the detection of perceptual information which, in turn, must guide the controllers of the neuro-muscular actuators. Hence the relevant potential difference, or *goal-gradient*, can only be defined over an interior (metabolic) potential relating the initial state of intending the goal to the final state of arriving at the goal. This gradient must

> also reflect the difference between a system's current manner of behavior *where it is* and the desired manner of behavior *where it wants to be*.
>
> The trick is to get the interior gradient and the exterior gradient linearly superposed so that their resultant is the desired goal-gradient. But this raises another problem. What kind of strange potential is the goal-gradient to be defined over? What is this superposed potential that is neither solely energy nor solely information but both? We call the resulting potential a *generalized action potential*. Whatever this generalized potential is, it is what flows in bi-temporal directions, between the interior and exterior frames, over the perceiving-acting cycle. Furthermore, it is also what must be *conserved* under the intentional dynamics of any system when successfully seeking a goal (pp. 595-596).

Here, we proposed a way that this 'trick' of superposition might take place. Furthermore, it was shown how such a generalized action potential might exist, as well as how such a quantity might be conserved (under the Liouville theorem) as a fundamental dynamical invariant of intentional systems.

On the other hand, this 'classical' approach failed to make clear how a particular goalpath is selected by the system from all causally possible goalpaths; rather we described mathematically only how the perceiving-acting cycle might move down *which ever* goalpath was selected. As in our original paper [7], the 'extraordinary boundary conditions' posed on a dynamical system by the selection of a goal are not defined, only assumed. In the present paper we seek to remedy this problem. Here we offer an explicit mathematical description of how an actor's intention to pursue a goal automatically does two things: *First, the intention to act imposes the 'extraordinary' information and control boundary conditions on the action taken, and, second, the action selects if not the actual goalpath, then the most probable one to be followed.*

Furthermore, we need to show how getting the appropriate mathematical description of the generalized action potential assigns a probability value to each path in the distribution of potential goalpaths. The probability value provides a *likelihood estimate* of the path being selected by the perceiving-acting cycle as the 'best' route to the goal, given the confluence of environmental and biomechanical constraints. 'Best' here means the practicable compromise between the mathematically ideal and the physically achievable, what can be thought of as the *tolerably sub-optimal path* [7]. But how are information and control to be coupled to form a perceiving-acting cycle that can select such a goalpath?

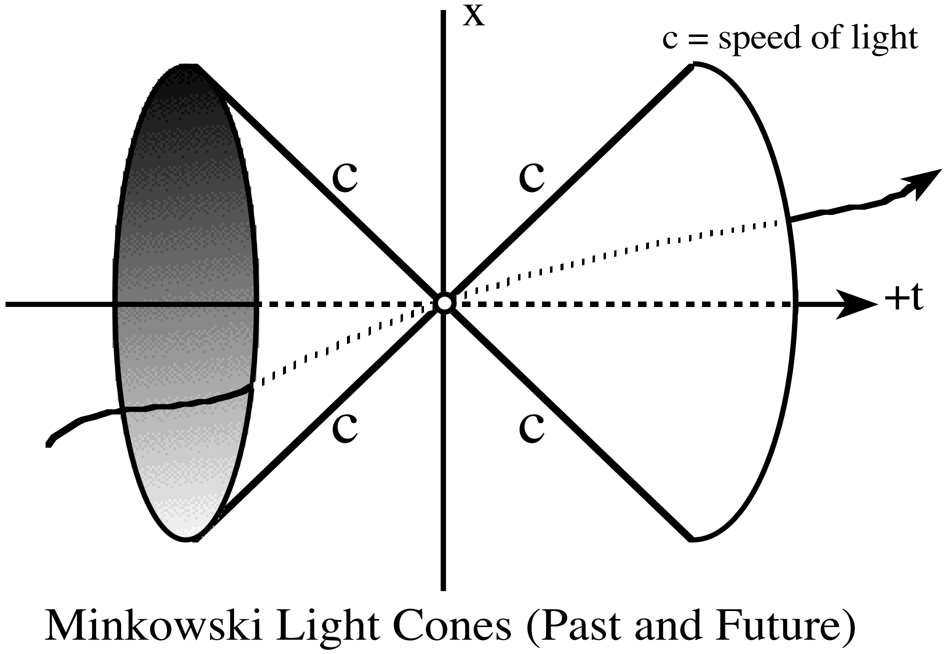

Figure 1. Minkowski Light Cones.

Figure 1 shows an unbounded worldline passing through an origin. Imagine all possible worldlines converging on the origin from the past that might be occupied by an actor. These are all the events that the actor might have perceived as well as all the past events that might have causally affected him. Also, imagine all the worldlines diverging from the origin toward the future. These are all the possible events that may originate from the actor—actions or information—to affect future events.

Between the moment of the intent to pursue a goal and the successful attainment of the goal, there exists a functionally defined, space-time region in which the intentional dynamics of the actor is well-defined. In four dimensional geometry any dynamical process is represented by an event which develops over a worldline segment. To understand intuitively the geometry in which goal-directed actions take place, one might first build a geometry for events [11]. For example, Figure 1 shows the standard light cone from the Minkowski rendition of special relativity. (Here the third spatial dimension is omitted). The backward temporal cone, called *the domain of (causal) influence*, indicates all those events in the past that might causally affect the event at the origin (vertex). By contrast, the forward temporal cone, called *the domain of (causal) dependence*, indicates all those events in the future that might be affected by the event at the origin.

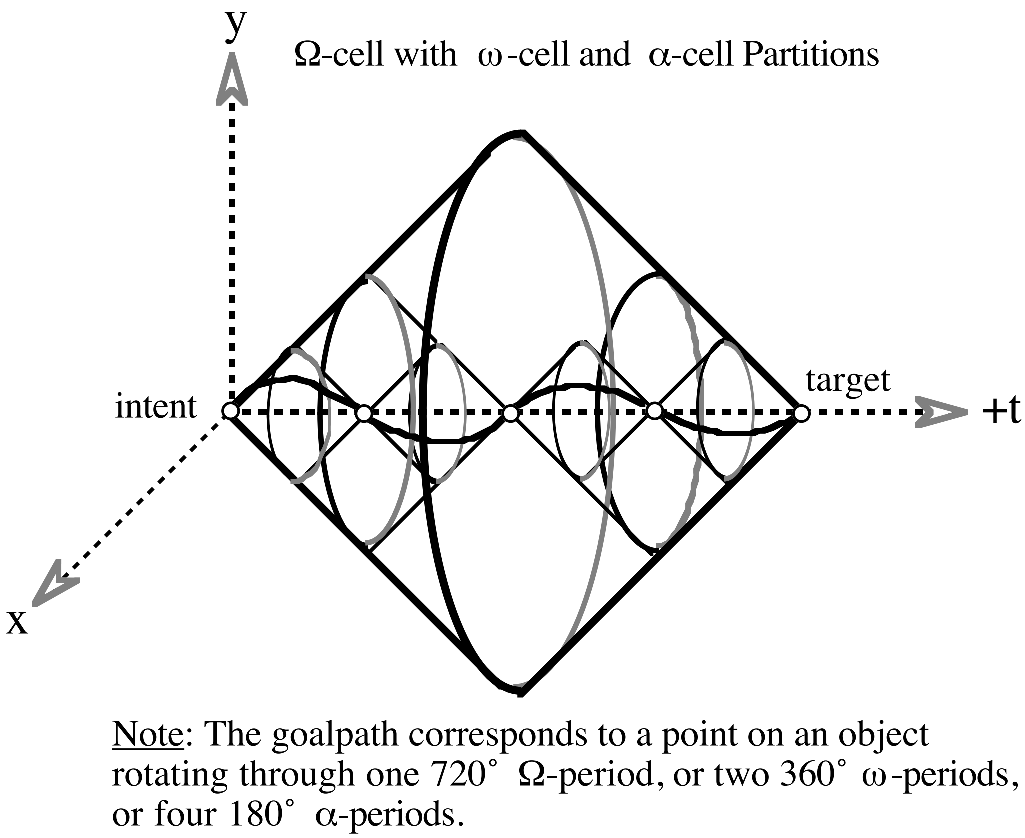

Figure 2. An Ω-cell Geometry for a Goal-directed Action.

Here we see that the worldline segment representing a goalpath is bounded by the point of intent and the target point. In between these endpoints are other points, called *choice-points*, at which sub-goals for subordinate actions are determined. The four ballistic half-turns of the turntable are represented as the points parsing the sinusoidal curve generated over space-time by the rotation event. (The accelerations and decelerations are not depicted).

The standard light cone is not adequate for depicting goal-directed behaviors since its worldlines are unbounded. Instead, we need a new four-dimensional geometry in which the worldlines representing goal-directed actions are bounded by endpoints. Figure 2 depicts this new geometry. Imagine, for sake of illustration, that you are given the task of spinning a turntable manually through four successive half-turns (4 x 180˚). The kinematics of this goal-directed action is shown below.

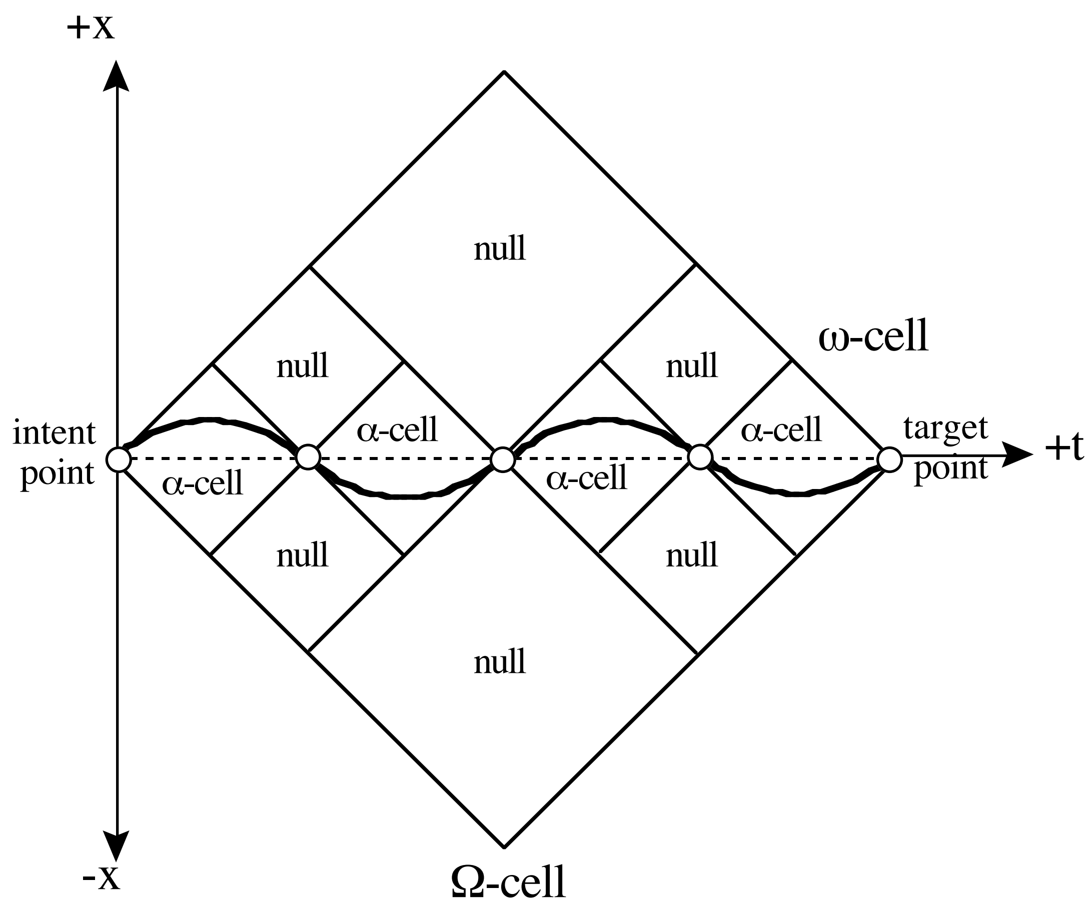

Figure 3: A Schematic Ω-cell Showing its Nested Partitions.

The *Ω*-cell's four dimensional geometry is a *lattice* structure, and therefore has three possible partitions (see Figures 2 and 3): the maximum partition, or *least upper bound*, noted by *Ω*-cell = ω_{max}, the minimum partition, or *greatest lower bound*, noted by *α*-cell = ω_{min}, and the intermediate partitions, noted simply by *ω*-cell = *ω*. Thus, in general, any form of goal-directed behavior will have a lattice structure within the geometry of the *Ω*-cell as indicated by

$$\Omega\text{-}cell = \omega_{max}\ {}^{3}\ \omega \geq \omega_{min} = \alpha\text{-}cell.$$

In the turntable task, the *Ω*-cell partition corresponds to the overall intention of rotating the turntable through 720˚; the *w*-cell partition corresponds to the subgoals of rotating through two full rotations (2 x 360˚); and the α-cell partition corresponds to the four 180˚ ballistic rotations (below which no choice-points are possible). A similar analysis generalizes to any goalpath with any number of partitions.

An *econiche* for an organism (or species) is defined by *how* it lives in its habitat. *Affordances* present opportunities for action since they are possible goals. The character of an econiche is determined by its affordance structure. Indeed, an econiche *is* its affordance structure. *Effectivities* correspond to the means required to carry out a control law by which an affordance goal is realized (what Gibson [2] referred to as *a rule for the perceptual control of action*). The repertoire of effectivities possessed by an organism determines what kind of actor it is. Indeed, an actor *is* its effectivity repertoire. In this sense, an ecosystem is the union of the affordance structure of an econiche and the effectivity system of an actor (or species of actors). A *situation* refers to *where* the relevant causal and informational constraints for an action exist. An *occasion* refers to *when* the need or value motivating the action is felt. An *effectivity* is brought to bear on an affordance goal when the actor *intends* to act so as to satisfy a motivating need or value.

All these ingredients (need or value, affordance goal, effectivity means, and intention, together with the implied forces to be controlled and information to be detected) must become a coherent unit of analysis if the intentional dynamics of an entailed action is to be understood. The theoretical construct under which all this comes together as an organized whole is, of course, *the Ω-cell*.

An organism's life as an actor is a 'tiling' of space-time by a concatenation of Ω-cells whose partitions parse the worldline of the actor from birth to death. Intentions are choices of affordance goals which functionally create the Ω-cells to be entered and hopefully crossed. The crossing requires the 'assembling' of an effectivity to engage, direct, and tune the appropriate perceiving-acting cycle to the exigencies of the task situation. The α-cell partitions of an Ω-cell represent the tolerance limits on information detection and energy control—below which a kind of Heisenberg uncertainty is encountered. The ω-cell partitions designate those choice-points in control where a bifurcation set of possible paths exists. Here the actor, given an up-date on perceptual information, can alter the manner of approach to a sub-goal without abandoning the global goal defining the parent Ω-cell. These are the minimal constituents that must be captured in any theory of the intentional dynamics underwriting goal-directed actions. These intuitions can be made formally explicit.

Although functionally defined, Ω-cells have an objective reality. They determine the boundaries on behaviors which are tolerant of the same goal (i.e., target plus manner). Such nonlocal goal constraints have the same ontological status as forces in physics, for which evidence is also only functionally defined as a relationship between masses and their observed accelerations (direction and speed). The tolerance class of goalpaths (i.e., each being a velocity field) are parametric (manner) variants whose underlying invariant is their common goal-directedness.

Where the *affordance goal* determines the final condition which constrains the resultant direction of the paths, the *effectivity* chosen determines which of the possible goalpaths within the Ω-cell is to be followed. Hence, in the case of a successful goal-directed behavior, an affordance goal—a functional property of the environment—is always complemented by an effectivity—a functional property of the actor. The intention, as a cognitive attunement operation, brings the necessary control and information to bear on the biomechanics of the actor. So long as the intention remains invariant, and *ceteris paribus*, the actor is perceptually guided down the goalpath.

4 Conclusion

Others have attempted to explain goal-directed behavior, but without the Ω-cell construct to consolidate the 'common fate' or 'determining tendency' of the variant but goal tolerant paths, little mathematical progress was possible [12] [13] [14]. By building our theory of intentional dynamics around this fundamental concept, we show how the perceiving-acting cycle might be situated in an intentional context.

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