

* Mathematize all claims
here (using Hawking & Ellis).

introduce 2nd order actions
by explicit examples of
CF treatment of wheelchairs
navigation of cat jumping
banking & helicopters.

ECOLOGICAL MECHANICS: A PHYSICAL GEOMETRY FOR INTENTIONAL CONSTRAINTS *

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Shaw, R. and J. Kinsella-Shaw, 1988. Ecological mechanics: A physical geometry for intentional constraints. *Human Movement Science* 7, 155-200.

A proposal is made for a new discipline, *ecological mechanics*. This version of mechanics is complementary but not reducible to classical relativity, and quantum mechanics. Where traditional mechanics attempt causal analyses for all motions, ecological mechanics explicitly addresses the motions of living systems that exhibit goal-directedness. The shortcomings of the physical geometries underlying traditional mechanics are reviewed, and means are proposed for redressing their deficiencies for modeling the behaviors of intentional systems. This demands a new physical geometry that retains all the best features of the old ones but is extended to accommodate intentional acts. The new physical geometry combines a variant of Minkowski's space-time geometry with a (Cantorian) fractal geometry which reformulates Einstein's *energy conversion law* ($E = mc^2$) and Planck's *energy distribution law* ($E = fh$) so that they apply, more realistically, to the scale of living systems. A new scaling technique called *ecometrics*, is introduced for accomplishing this feat. This approach assumes a symmetry operator which acts to 'intentionalize' causation and to 'causalize' intention so that perceptual information and action control processes are defined over a commensurate but dual measurement bases. The promise of ecological mechanics rests on the imputed discovery of a new conservation law which holds locally rather than absolutely. Empirical evidence is reviewed and graphically portrayed mathematical arguments are given that tend to support the hypothesis.

• We wish to express our deep appreciation to Peter Kugler for sharing his insights and helping us express the essentials of our program; to Michael Turvey whose encouragement and natural eloquence helped us improve the manuscript. Without Kugler and Turvey, whose recent book blazed a trail we could follow, it is unlikely this paper would have seen the light of day. Consequently we dedicate this paper to them.

Our thanks to Thomas Barribeau for his generous help in many phases of the production of this manuscript and to Mary Kinsella-Shaw for help in preparation of the bibliography.

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Ecological mechanics: Laws scaled to intentional systems

No actions escape accountability to natural law. Actions occur at three fundamental scales. The upper-most bound is set by the speed of light at the astronomical scale of relativistic mechanics, while the lower-most bound is set at the particle scale of quantum mechanics by Planck's constant. A third scale exists which falls between these two fundamental scales. This is the scale where living systems carry out goal-directed behavior – a different kind of action mechanics than that possible at either of the other two scales. This 'in-between' scale we shall call the *ecological scale*, and measurement at this scale – *ecometrics*.

Einstein's famous energy conversion equation, $E = mc^2$, provides the upper-limit of ideal conversion of the potential energy of a mass quantity into the work that can be done by kinetic energy over a region of space – time. But this is not useful work because it is not directed toward any goal. The energy, ideally, is released as a burst at the speed of light. To be unconstrained means to be uncontrolled; hence no useful work. Clearly, this unmitigated action at the relativistic scale is not appropriate for modeling the actions of living systems. Actions at the ecological scale are produced by the carefully controlled release of metabolic energy that conserves the body's mass – not in a single burst at light speed that consumes its mass.

Planck's equally famous quantum equation, $E = fh$, provides the lower-limit on ideal energy distribution as impulses over a path in space–time. But again these are not useful impulses because they are not directed toward any goal. The paths of these impulses are randomly scattered through a region of space–time. The aimless actions at the quantum scale make it inappropriate for modeling the goal-directed actions of living systems. Actions at the ecological scale are produced as carefully packaged and concatenated bundles of impulses – not random bursts of quantal size.

At the ecological scale we must have an analogue of energy conversion, but it can not be an uncontrolled burst. And we must have an analogue of quantum distribution, but it can not be random. Note that the deficiencies of the super-macro scale of relativistic mechanics and the super-micro scale of quantum mechanics for modeling goal-directed behavior are *complementary*. The outer-scale deficiency of relativistic mechanics is redressed by considering actions confined to a region of

space–time smaller than that determined by the speed of light. The inner-scale deficiency of quantum mechanics is redressed by considering actions to be along paths whose steps are larger than a quantum. In spite of these deficiencies, however, we can not do without some form of energy conversion and energy distribution at the ecological scale. But we must rescale these extrema toward the middle range of 'ecological' mechanics to make effective control possible.

The ecometric solution is to construct formal analogues to the energy conversion equation and the energy distribution equation at the scale of goal-directed behavior. It does so by a convergent rescaling from the extrema toward the middle scale. This is accomplished by employing the dual scaling operations of *interpolation from the outer-scale* and *extrapolation from the inner-scale*. Mathematically speaking, ecometrics must solve a two-point (nonlinear) boundary problem (for nondifferentiable systems). The purpose of this article is to propose such a solution. Intuitively, this can be envisioned as packaging upward from the quantal scale and partitioning downward from the relativistic scale to a scale relevant to living systems.

We propose to call the extrema, that is, the *greatest-lower-bound* and the *least-upper-bound*, on any scale, the α -tolerance limit and the Ω -tolerance limit, respectively. As pointed out earlier, the tolerance limits on inner and outer scaling in physics are set by Planck's constant, h , and the speed of light, c . The ecometric approach is directed toward the discovery of the α - and Ω -tolerance limits for psychology and biology within the bounds set by physics of both extremes. (See fig. 1.) Central to ecological physics is the conviction that accounts of psychological and biological phenomena must be consistent with but not reducible to physical law. This approach leads to a view of laws at the ecological scale that cover both biology and psychology. Such laws must have a graded determinism that is neither so absolute as relativistic laws nor so relative as quantum laws (Weiss 1969; Wigner 1969).

Einstein's view was that measurement has no effect on what is measured. Bohr, the father of orthodox quantum theory, disagreed. Instead, he argued that measurement is an act that makes definite the states of particles which are indefinite until measured. For Einstein perception and action are disjoint in the act of measurement: One may see without altering what is seen. For Bohr perception and action are conjoint in the act of measurement: By seeing one alters what is seen.

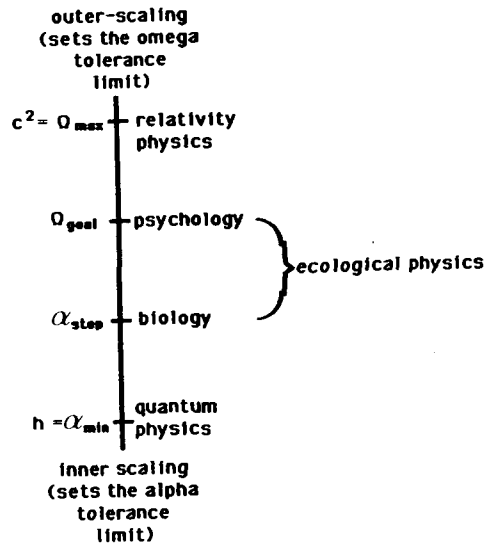


Fig. 1. Determining the relative inner (α) and outer (Ω) scales of ecological physics.

Ω_{\max} is the maximum omega tolerance limit on the energy conversion law $E/M = c^2$ (where E = energy, M = mass, and c = speed of light). c^2 is a region of space-time that kinetic energy fills at the speed of light when potential energy, in the form of a unit quantity of mass, is perfectly converted. Rescaling inwardly we arrive at the Ω_{goal} , the maximum tolerance limit on the carefully controlled conversion of a fixed quantity of potential energy, a unit quantity of biomass, into the kinetic energy needed to satisfy a goal-direction action. Here α_{step} is the minimum size of a metabolic energy 'squirt' required to move an organism one step toward the goal. And, finally, α_{min} is the absolute minimum size any energy squirt can be. This of course corresponds to Planck's energy distribution law for quanta, $E = fh$ (where h = Planck's constant and f = frequency). Just as

$$h = E/f = \Omega_{\text{goal}}/f = \alpha_{\text{step}},$$

so by rescaling we have

$$\Omega_{\max}/f = \alpha_{\text{step}}$$

(here f is defined as *distance to goal in step-cycle periods*).

The main job of ecological physics is to show how energy conversion and energy distribution laws may be tailored to the scale of living systems so as to make their behaviors not so exceptional as to defy a natural (ecological) physical interpretation. This will be done, however, without philosophically reducing the problem of intended movements to mere caused motions.

The middle ground of ecometrics reconciles these polar positions. Here perception and action are, in one sense, conjoint and in another sense disjoint. At the scale of living systems, perception and action are conjoint in that they serve a mutual aim – the satisfaction of a goal; they are disjoint in that they serve that aim in reciprocal ways – by the *detection of information* that constrains action and by the *control of actions* that produce changes in perception. In a circularly causal manner, perceiving alters action and acting alters perception while leaving the motivating intention unaltered until the aim is accomplished. This *circular causality* makes the modeling of goal-directed systems problematic from the point of view of traditional physics. Why this should be so is the first topic to be discussed.

Requirements of goal-directed behavior

Outstanding examples of goal-directed behaviors are locomotory cases where actors must use perceptual information to guide their behaviors. For instance, a cat sees a distance to jump to reach a perch on a fence and does so in a single, visually-guided, ballistic movement. Or the driver of a car carefully modulates the brake pressure to slow down and eventually stop at a stop sign. Or a marathon runner assiduously controls his/her running speed to maintain a smooth, steady, sane pace so as to avoid premature 'burn-out', thus enabling him/her to complete the 26.2 mile course. In each of these cases the actors must detect and use, in near optimal fashion, goal-specific information to control their actions. What are the common requirements for actors to achieve successful goal-directed behaviors? Whatever these requirements may be they are dictated by the selection pressures of evolution, placing them squarely in the conjoint domain of psychology and biology. We take this domain to be that of ecological physics as shown in fig. 1.

The ease with which organisms set and attain goals contrasts sharply with the difficulties invariably encountered by efforts to understand the means they employ. Organisms regularly and reliably use information in the control of actions that culminate in the satisfaction of their goals. The regular and reliable satisfaction of goals is essential if an organism is to survive. Organisms that consistently fail to satisfy some irreducible set of goals dictated by their psychological needs inevitably

perish. Organisms with high rates of success, measured as acts that terminate in the satisfaction of their goals, are characterized as 'well-adapted' or 'fit' to their environmental niches. Such organisms thrive as individuals and species. The basis for a good fit between an organism and its environment rests on the organism's ability to exploit the information in the environment.

This is not so simple a statement as it may first appear. It entails an organism evolved to detect information that specifies both the organism's current relationship to its environment and the potential relationships it can choose to enter into. Additionally, the organism must be sensitive to the information that can support those actions that will carry it from its current state (where *state* is taken to mean relationship to the environment) to its desired state, or *goal*. That is, organisms must be able to detect information in their environments that tells them where they are, where they can go, when they can go, and how they can get there.

This means the organism must have information specific to the control of its actions and goals. Such information, then, provides the organism with a measure of how much work it must do if the goal is to be realized. In sum, the organism must be able to *detect* goal-specific information, *allocate* the necessary 'on-board' energy resources, and *control* the expenditure of these resources in a preferred manner that will bring it into the targeted relationship with the environment. These are the requirements for goal-directed behaviors to be successful. In the course of this paper, we will explore a scheme for modeling the means by which organisms are able to satisfy these requirements. These requirements are met mathematically by discovering the alpha (α) and omega (Ω) limits on goal-directed behavior.

The selection of a goal by intention sets the Ω -limits while the α -limits are defined as the limits on the resolution of information detection and the precision of action control.

Role of intention in action: Setting the Ω -limits

Intention has both vague philosophical and puzzling psychological interpretations that are at best, under current theorizing, problematic and legitimately debatable. However, the logical role of intention common to all such theories can be stripped of semantic considerations

to reveal its mathematical skeleton, so to speak. Treated as a mathematical operator, intention has duties to perform which may be made explicit even though the mechanism is left in the shadows of our science. Put simply: We shall not attempt to say what an intention is, nor from whence it hails, but only what it does. Thus, in this sense, intention is a logical primitive whose sole role is to establish final conditions by selecting an environmental target and the preferred manner of approaching that target. Perhaps, a fuller understanding and appreciation of the consequences of intention as an extraordinary physical constraint will provide us with sufficient rudimentary understanding to eventually launch a more comprehensive scientific investigation into its nature and origins. What then do we minimally need to say about the role of intention?

Intentional systems, because of goal-dependency, are traditionally said to be *teleological* rather than merely causal. However, teleological theories are typically interpreted as requiring a future goal-state to act backwards in time to direct the forces that causally produce progress toward the stipulated goal. Accounts that depend on temporally backward constraints, since they violate the usual order of cause and effect, lack scientific credibility. Credibility might be established for such theories if a mechanism were introduced that explains how future conditions of a system might modulate its past conditions. As we shall try to show, this is exactly the role to be played by perceptually informed intention. But to do so calls for a reinterpretation of the term 'teleology'.

Many contemporary scientists have attempted a reformulation of teleology along the following lines: Natural systems that have intentions have the capability to select goals. If they also have the realistic means to attain those goals, then they are said to be causally *teleomatic* – that is, proceeding by physical law (Mayr 1976, 1982). Being causally teleomatic in no way implies that the system is aware of the goals or of the selection process – only that it selects goals that it can realistically act toward. On the other hand, *teleonomic* implies that the physical causal basis for goal-directed behavior is not sufficient; there must be something more. In addition, there must be a *rule* that initializes the causal laws governing the teleomatic process. The exact nature of this rule, however, is rarely spelled out. For our purposes, we take all goal-directed systems to be teleomatically *driven* but teleonomically *directed*. Many scientists have made valiant attempts to clarify the

intention as an operator

teleology, no!
teleonomy, etc

teleomatic
driven and
teleonomic
directed
(Gastel vs info)

relationship between causal and teleological explanation in science – seeing both as legitimate and necessary to a complete theory of living systems (Sommerhoff 1950, 1974; Weir 1984; Rosen 1985; Oyama 1985; Kugler and Turvey 1987; Shaw 1987).

We take intention to be goal-selection which sets up the tolerance limits on the Ω -cell relevant to the scale of living systems. Once we understand the role of intentions, we will then have a basis for ecometrically defining the ecological version of the energy conversion law. The origins of intentions is a formidable issue that we shall leave to the evolutionary philosopher. However, intention has an active role to play in the genesis and control of everyday actions. Indeed, one might say it provides the dynamics for behavior and sets its boundary conditions. (See Kugler and Turvey (1987: ch. 13) for a detailed discussion of this caveat.)

Action directed towards the satisfaction of a goal differs from mechanically produced physical motion as treated in classical physics. Even though one can characterize both physical motions and an organism's goal-directed actions as having initial conditions, final conditions, and spatio-temporal paths described by boundary conditions, there are, nevertheless, fundamental differences (Kugler et al. 1985). In classical mechanics, equilibria systems are assumed to behave linearly, with trajectories that are ideally smooth and, therefore, differentiable. Particles with virtually the same initial conditions that begin traveling together are likely to end their journey together – barring outside influences and a little random error. Such ordinary systems exhibit stable behaviors that can be expressed by and predicted from differential equations. Thus classically stable systems show a *virtual insensitivity to small errors in initial conditions*.

Contemporary dynamical systems theorists now recognize the mistake of overgeneralizing the analytic ideals of classical mechanics; they, now recognize that many natural systems are nonlinear. For instance, particles attracted to simple *point-attractors* or *periodic-attractors* (e.g., limit-cycles) – may have had quite different initial conditions but still end up in the same stable final condition. In other words, in sharp contrast to classical systems, nonlinear systems trapped by the same attractor dynamics show an *insensitivity to initial conditions but coincidental final conditions* (Abraham and Shaw 1983a).

Other systems behave in nonlinear fashions so unpredictable a priori that, even if their differential equations could be written, they probably

could not be solved. Furthermore, whatever, laws such systems obey must be experimentally revealed, typically, by huge iterative programs driving clever computer-graphic animations. Predictability of such nonlinear systems may be impossible but post hoc description is proving most elegant. Such systems are said to be 'chaotic' and to have trajectories determined in complex ways by what are called 'strange' attractors (Abraham and Shaw 1983b; Cvitanovic 1984; Gleick 1987). These nonidealized systems, in contrast to their less sensitive periodic cousins, are most eloquently described as exhibiting *sensitive dependence on initial conditions*: Points that begin close to each other, sharing nearly but not exactly the same initial conditions, may eventually end up very far a part.

Intentional systems provide an important but often overlooked contrast to both classical linear systems and the more complex nonlinear systems. Intentional systems are capable of aiming themselves by authoring, in part, their own initial conditions. Unlike ordinary systems, that must be aimed by extrinsically imposed initial conditions, or pulled by a pre-existent attractor, intentional systems literally aim themselves toward targets. They impose their own initial conditions and change them when they feel satisfied – sometimes in cooperation with environmental conditions but often competing with them. Thus instead of showing virtual insensitivity to small errors in initial conditions (as classical systems do), or insensitivity to initial conditions, (as periodic attractor systems do), or the extremely sensitive dependence on initial conditions (as 'chaotic' systems do), intentional systems, show both a *significant insensitivity to extrinsically imposed initial conditions* as well as an *uncommon sensitive dependence on final conditions*. All roads lead to Rome if one intends that goal; obstacles may be overcome, force gradients traversed against the grain, because intention somehow creates its own attractor basins.

Hence intentional systems do not quite fit the description for any of the systems ordinarily studied. And, yet, luckily, they are not completely unrelated either. The profound problem that faces the intentional systems theorist is how sensitivity to final conditions can be a concurrent concern with its initial conditions. It would be a mistake, however, to read this as the demand that sensitivity to a final conditions itself be considered just another initial condition, for then there would be no goal-directedness (Weir 1984). Goal-directness is a global

teleonomic constraint, a boundary condition, that cannot be reduced to local teleomatic steps.

Recognition by traditional psychological theorists that goal-directed behaviors are inexplicable by the laws of classical mechanics, or even the general principles and symmetry relations that sit behind physical science, have led them to abandon the law-based strategy of natural science and to substitute in its wake a *rule-governed* approach to behavior (Gardner 1985). Rule-governed approaches attempt to obtain an acceptable teleomatic analysis of goal-directed steps by postulating an arbitrary number of local teleonomic constraints – cognitive ‘rules’. Motor ‘programs’ are such an instance (see Schmidt 1982).

In short, because goal-directed behavior has so far eluded a lawful analysis, the field is in danger of becoming increasingly isolated from the other natural sciences which depend on law-based analysis. Perhaps, this is so because theorists have tacitly but correctly assumed that the lawful strategy of Newtonian physics and Euclidean geometry is not up to the task. We agree. These traditional conceptual tools are quite inadequate for modeling the behavior of intention-directed systems. We disagree, however, with the conclusion that the only remaining strategy is to adopt a *rule-based* account which separates psychology and biology from the rest of natural science. Let us examine the inadequacies of the Newtonian/Euclidean account before offering what we believe to be a viable alternative physical geometry for intentional systems.

This classical physical geometry does not provide α - nor Ω -tolerance limits on any physical phenomena. In Newtonian *space and time*, physical systems can act instantaneously, violating the laws of relativity that assert that the speed of light sets the upper velocity bound on all objects with a non-zero rest mass. Furthermore, under the Newtonian characterization, the mass of a physical system can be concentrated at a point taking up no space in defiance of the laws of quantum mechanics (see fig. 2). Obviously, a physical and geometrical scheme that allows for such unrealistic entities as *volumeless masses that act instantaneously* is too unconstrained to be useful in describing the behavior of living systems. Such a theoretical framework fails to set the boundaries on the extrema of realistic physical phenomena, and so is completely inadequate for the in-between scale of ecometric analysis that attempts to discover the optima. This does not mean, however, that we should abandon attempts at a lawful analysis of goal-directed behavior but,

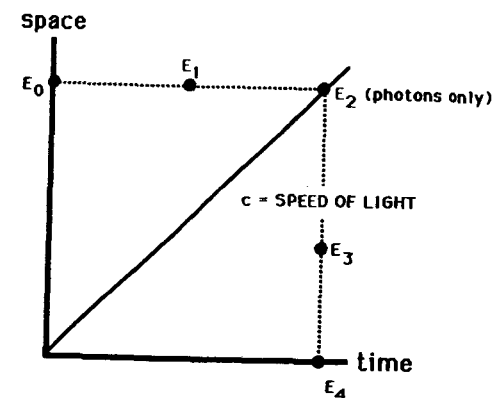


Fig. 2. Newtonian space and time.

The Euclidean distance measure

$$\Delta d = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2 + \Delta t^2}.$$

- E_0 = instantaneous event,
- E_1 = faster than the speed of light event,
- E_2 = speed of light event,
- E_3 = slower than the speed of light event,
- E_4 = no motion at all (i.e., object at rest).

All of the above ‘events’ are possible in this classical ‘event’ geometry. E_0 and E_1 violate the laws of relativity that assert that c is the limiting velocity in the universe for all objects with a non-zero rest mass. Only photons can travel at the speed of light because they have no rest mass.

rather, that we should seek a more naturally constrained physical geometry.

Demands of a physical geometry for goal-directed behavior

Goal-directed behavior differs from aimless, mechanically produced, physical motion in several ways. As classically defined, mechanically produced motions are linear, or analytically continuous, conservative, and holonomically constrained. (See Rosen, this issue). For such motions to become aimed all of the above properties are violated in interesting and systematic ways because an actor’s intentions are necessarily implicated. Unlike a mere motion, an aimed movement is nonlin-

- ✓ ear, in the sense of being nonanalytically continuous because of bifurcations due to potential choices. It is also nonconservative (in the classical sense) because it is path-dependent; the forces that select directions are dictated by intentions not by prior forces. And, lastly,
- ✓ aimed movements are nonholonomic in that they depend on nonintegrable constraints, that is, on currently available anticipatory information about future goal-states (Weir 1984; Rosen 1985; Pattee 1972).

To reiterate: Classical physical geometry has deficiencies that make it a poor choice for modeling goal-directed behavior. A more adequate physical geometry will remedy these deficiencies by introducing countering constraints. For instance, the deficiencies of the idealized geometry of Newtonian physics that allows for instantaneous actions of volumeless masses arise because space and time are held separate (as shown in fig. 2). A better physical geometry has been offered by Minkowski. His geometry, as adopted by Einstein, disallows these unrealistic properties by melding space and time into a single system of measurement (fig. 3). This system of measurement is appropriately called the *space-time continuum*. Note that within this spatio-temporal scheme there are no events or objects that do not occupy a finite region of space-time. This means that the movements of living systems, like the motions of mechanical systems, now must abide by the α - and Ω -tolerance limits of natural law. These provide special boundary conditions that have no place in the traditional analytic techniques of classical physics.

But of course the Minkowski space-time geometry does not offer a remedy to all the deficiencies of classical physical geometries with respect to our problem. Its major deficiency is that it is too open-ended; it too requires some special boundary conditions. In this geometry one may define the indefinite causal future of a system (fig. 4) or the indefinite causal past of the system (fig. 5). One can even coordinate the causal past of a system with its causal future to create a complete teleomatic history – called the system's *world-line*. This can be illustrated by splicing figs. 4 and 5 as shown in fig. 6. But one cannot define the boundary conditions on a past state that is intentionally related to a future state. By means of anticipatory information, as system's behavior can be directed in an intended manner toward a selected target. Satisfaction of this latter requirement must invoke a teleonomic constraint. Such a *teleonomic constraint* can be mathematically defined as an *operator* that achieves a higher-order melding of

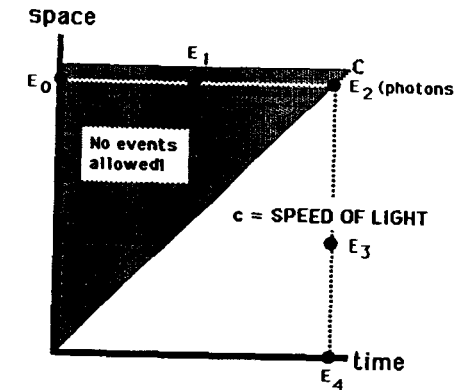


Fig. 3. Two-dimensional section of a four-dimensional spacetime.

The Minkowskian distance metric

$$\Delta d = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2 - \Delta t^2}.$$

- E_0 = instantaneous event (*not allowed!*),
- E_1 = faster than light event (*not allowed!*),
- E_2 = speed of light event (*photons only!*),
- E_3 = slower than the speed of light event (*o.k!*),
- E_4 = no motion at all (i.e., object at rest) (*o.k!*).

The velocities of light sets the upper-limit on all velocities of objects with rest mass. Also there are no events that do not take-up both space and time. *Note:* In the Minkowski distance metric temporal sign is *negative*. This contrasts with the Euclidean distance metric which is positive, as shown in fig. 2.

'Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.'

(Minkowski 1908).

some definite past of the system, wherein an intention arises, with some definite future goal-state, which it strives to attain. (How this operator effects the melding of the two geometric perspectives is shown in fig. 7.) We might dramatize the novelty of the resulting physical geometry, wherein intentions and goals set the exceptional boundary conditions on purposive 'motions', by rephrasing Minkowski's (1908) lyrical remark about his own space-time melding operator (see quote, fig. 3) as follows:

Henceforth past intents by themselves, and future goals by themselves, are doomed to fade away into mere shadows, and only a kind of union of the two into an Ω -cell will preserve an independent reality.

*an action for
rather than
a state to
state transition
of the whole
etc.*

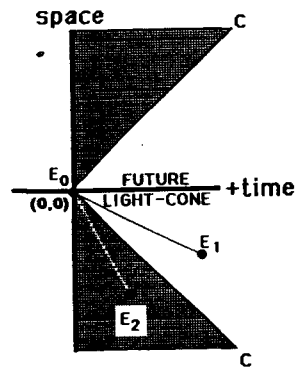


Fig. 4. The future light-cone.

All points in this space are events because they have both space and time coordinates. The path connecting two events, such as the line between E_0 and E_1 , is called a *world-line*. Here E_0 is in the past of E_1 while E_1 is in the future of E_0 .

Not all events, however, can be so connected. None of the events in the null cone can be connected by a world-line to events in the future light-cone because they are effectively simultaneous and can not causally interact. For instance, E_2 is simultaneous with E_0 and E_1 . The minus sign in Minkowski's equation (see fig. 3) makes the speed of light, c , the asymptote for the world-lines which form a hyperbolic set of events reachable from E_0 .

What an adequate physical geometry must accomplish is a mathematical means for 'mechanizing' intention (the teleomatic problem) and 'intentionalizing' causation (the teleonomic problem). In their recent book, Kugler and Turvey (1987) present the most complete law-based account to date of the physical biology of goal-directed behavior. In their account they assert:

'In very blunt terms, the content of a person's intention (approximately, the desired act) is tantamount to an exceptional boundary condition that harnesses the lawful relations and fetters the use of resources [for the production of a goal-directed behavior].' (Kugler and Turvey 1987: 405)

We might ask how the system obtains the goal-specific information that acts as exceptional boundary conditions for a given goal-directed act. These exceptional boundary conditions are set by the intentional selection of a goal. They are Ω -limits relative to the ecological scale and will be given the name Ω -cell, as introduced above. Thus, the Ω -cell contains two components of any goal-directed activity: First, it speci-

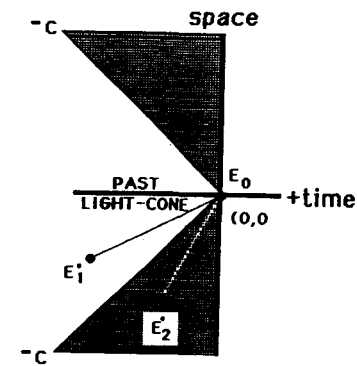


Fig. 5. The past light-cone.

The points in this space represent events in the causal part of E_0 . Here E'_1 is in the past of E_0 while E_0 is in the future of E'_1 . As before, none of the events in the null cone can be connected by a world-line to events in the past light-cone because they are effectively simultaneous and, therefore, can not causally interact. For instance, E'_2 is simultaneous with E'_1 and E_0 . As noted earlier the speed of light, c , is the asymptote for the hyperbolic set of events in E_0 's past from which it is reachable.

ifies the available environmental information that might be used in an anticipatory manner to direct an actor's course toward its selected goal; and, second, it defines all possible means for allocating an organism's on-board resources in the service of the stipulated intention.

Minkowski's contribution was to meld space with time in such a way as to make connections (world-lines) among events causally realistic. This higher abstraction was a vast improvement over ordinary physical geometry. In the same spirit, by our melding of a dual pair of Minkowski geometries to create still a higher-order geometry, we hope for an analogous improvement. For by this melding of a pair of *temporally complementary* event spaces, we achieve a more abstract space-time. This new space-time can now accommodate intentional as well as causal connections among initial and final states of a system's behavior along its preferred world-line.

Where the space-time of Minkowski is partitioned over events, this *dual Minkowski space-time* is partitioned over Ω -cells - space-time regions, wherein intents meld with goals when the intervening activities are successful.

implication
action under
a FDT description
of process (i.e.
temporal dynamics
principles as
goal-directed)

intentional
action like goal
directed, etc.

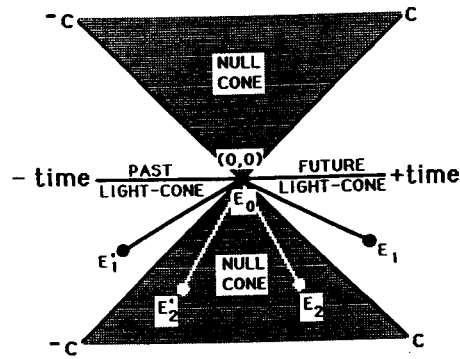


Fig. 6. The dual light-cone.

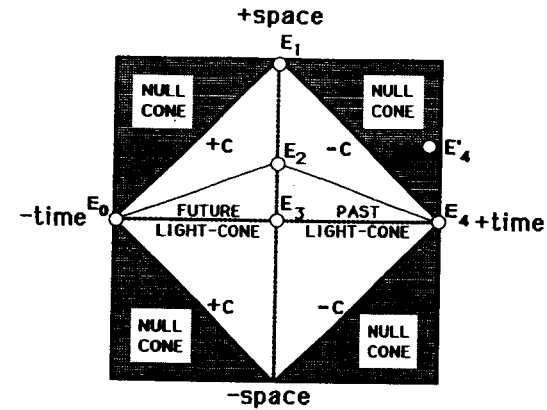
$E_1' \rightarrow E_1$ = causally possible world-line,
 $E_2' \rightarrow E_2$ = causally impossible world-line.

Here we see better how the speed of light, c , defines the forward and backward asymptotes for the dual halves of the cone. As noted, these hyperbolic sets give the possible past (E_1') and the potential future (E_2') of the world-line for E_0 as it winds through space-time from the past to the future.

The points in this space represent events in both the causal past and causal future of E_0 . By simply interchanging the signs for the temporal term (i.e., exchanging $+t$ for $-t$, cause for effect), all of the mathematical theorems that are true about the past are also true as dual theorems about the future. Thus, they are called 'dual (half-) cones. Logically speaking, event space-time is time invariant because the cones, being hyperbolic sets are symmetrical. So long as the field of events satisfies a Hamiltonian treatment, that is to say, is a conservative mechanical field, then the 'arrow of time' is reversible.

Later we shall see that the reversibility of the arrow of time in a conservative field will play an important role in ecological physics. For it is this possibility that will allow information and energy to coalesce as dually conserved quantities whenever a goal-directed behavior is successful.

- ✓ But this higher-order, intentional event space-time has its own glaring deficiency; it sets only the outer-limits on goal-directed behavior. It speaks only to energy conversion, and says nothing yet about the inner-limits on the ecometric scaling problem. It says nothing about how such Ω -cell energy is to be released in controlled α -steps. The same Ω -cell also confines the bounded set of world-line intervals that must be traversed in a controlled manner if a specific intent is to be realized.
- ✓ An ecometric solution to this resource allocation problem demands an inner-scaled energy distribution law (momentum conservation), like that proposed by Planck but less extreme, and an outer-scaled energy conversion law (energy conservation), like that proposed by Einstein but also less extreme.

Fig. 7. The omega (Ω) cell.

Take two events, E_0 and E_4 , and define the future cone of the earlier event and the past cone of the later event. The null cones of each dual half cone then determines a region bounded at its edges by the velocity of light. Let us call this region whose area is c^2 an *omega* (Ω) cell.

Any world-line connecting a pair of earlier and later events must lie somewhere within an omega cell of some determinate area (or volume for a three-dimensional space-time, or a hypervolume for four dimensional space-time).

Consider the world-lines: (Notice: All of the objects end up where they start from: that is, E_0 and E_4 are the same place at different times):

- (i) $E_0 \rightarrow E_3 \rightarrow E_4$ is an object at rest (i.e., no space intercept) over the time allotted;
- (ii) $E_0 \rightarrow E_2 \rightarrow E_4$ is an object that does a round trip at some velocity less than the speed of light;
- (iii) $E_0 \rightarrow E_1 \rightarrow E_4$ is an object that does a round trip at the speed of light (necessarily a photon).

In short, the laws of ecological physics must serve the 'in-between' scale of living systems. Could these local laws of ecological mechanics, that depend on energy/information conservation, be simply a regression toward the mean (the in-between') on the cosmic scale of global mechanics - a cosmic scale whose outer- and inner-scaling extremes are bounded by energy and momentum conservation, respectively? We think so, for all the reasons that follow.

Target and manner parameters

An Ω -cell is functionally defined when an actor intends a causally attainable goal. Intention, as a mathematical operator, performs the job

of setting the geometric and temporal parameters for a selected goal. This is done as follows. Goals are divisible into dual sets of parameters: target parameters and manner parameters. *Target parameters* kinematically define what is to be dynamically approached, such as a target-object or a target-event. In other words, this sets the final event terminus of a Minkowski world-line (e.g., E_4 of fig. 7). Target parameters consists of *direction-to-contact*, *time-to-contact*, and *distance-to-contact* to the final state. *Manner parameters* kinetically define how the approach to the final state is to be made (e.g., slowly and smoothly, or quickly and jerkily). Thus manner of control sets the path of the world-line through the Ω -cell. The set of manner parameters consists of *torque-to-contact*, *impulse-to-contact*, and *work-to-contact*. It can be shown that these parameters are mathematically *conjugate* terms (much the same as generalized coordinates and generalized momenta are in Lagrangian mechanics).

The dual specification, or conjugacy, of target-parameters and manner-parameters can be understood as follows: The *distance* one has to go specifies the *work* to be done in order to contact the target; target *direction* specifies the *moment of torque* required to turn the body into the proper heading; and the desired *schedule* of rendezvous with the target specifies the schedule of *impulse forces* that must be applied to do so. Hence the goal-state is not a static place, nor a simple state to be reached. Rather a goal-state is a dynamically specified 'window' in space-time, the parameterized Ω -cell, through which a targeted state is reached in a preferred manner.

An ecometric solution to the resource allocation problem for goal-directed behavior is to find a common denominator for these kinematic and kinetic variables that renders them dual. As they stand, it is like comparing apples to oranges. To make them dually comparable, then, figuratively speaking, some higher-level of analysis must be found where they may both be treated as fruit. An important result of finding a level where two different kinds of variables may be rendered dual is that if one member of the dual pair of parameters is specified, then so is the other. For instance, seeing the distance to walk (an information variable) is somehow equivalent, under the duality scheme, to seeing the work required to cover the distance (an energy variable), and so forth. There is evidence that such dual specification is more than a mere abstraction.

Experimental examples

We now turn our attention to two studies of human locomotion. It is hoped that a review of these studies of the initiation of gait will clarify the dual roles of manner parameters and target parameters in the modeling of goal-directed behaviors. Specifically, these experimental examples will be used to illustrate how intending some goal-specific parameter entails the perceptual specification of the boundaries of an Ω -cell. The solution to the resource allocation problem follows from this fact.

Manner only goals

In the first study, the relationship between an intended manner of acting and the assembly of the means to achieve that goal is investigated. Cook and Cozzens (1976) looked at the change in muscular activity at the ankle as a function of intended rate of locomotion. Ten subjects at rest were asked to walk at a preferred rate for a block of trials, to walk progressively slower with each trial for a block of trials, and to walk progressively faster for another block of trials. In each condition the subject was instructed to achieve a steady-state velocity as the goal-state criterion for concluding a given trial. Employing a force plate, measures of horizontal impulse forces generated at the ankle on the stance-side (the weight-bearing side) were taken at the initiation of gait. In addition, Cook and Cozzens took measures of stiffness at the ankle, defined as the *change-in-moment-per-change-in-angle* (in units of Newton-meters-per-radian).

From these measures it was concluded that a subject's goal to locomote in a particular manner, where a change in manner corresponds to a change in steady-state stride frequency, 'mechanized' the intention in terms of a change in ankle stiffness. In other words, it was found that the intended velocity (manner) necessarily marshals the neural and skeleto-muscular elements. Or, conversely, the actor's intention in selecting a (manner) goal assembles a physical cooperativity that is supported over the biological substrate of the actor. In this way, the intention imposes an exceptional (teleonomic) boundary condition over the actor's biological machinery. (This might be referred to as the *intentionalizing of causation*.) The imposition of these goal-relevant boundary conditions takes the form of changes in myoneural activity which combine with gravitational forces to effect adjustments in

torque-angle relationships, or stiffnesses, at the ankle. Prior to the first foot leaving the surface of support, the stiffness assembled permits the muscular generation of horizontal impulse forces sufficient to change the velocity of the center of biomass. This is expressed as local teleomatic constraints. These constraints generate a sequence of appropriate momenta changes in the α -steps which sustain the intended steady-state velocity.

In sum, the relevance of this study to understanding the resource allocation problem is in the finding that the stiffness assembled under the aegis of the intent to locomote in some manner was, indeed, a linear predictor of the manner of locomotion actually observed. Thus, intending a future goal-state allocates the necessary resources before the first step is ever taken toward the goal. This is a concrete illustration of how an intention, acting as a mathematical operator, sets the boundaries of an Ω -cell and then partitions this global teleonomic constraint into a temporal sequence of goal-directed local teleomatic steps.

Target only goals

In the example just given, the goal was a locomotory manner with no specified environmental target. By contrast, in this second example (Thompson 1983) the goal was to locomote to an environmental target with manner unspecified. People were asked to walk to targets over a flat terrain that were placed from three to twenty-one meters away. In the first condition, subjects were allowed to visually sample the target for five seconds before walking toward them blindly. In the second condition, subjects were allowed continuous visual sampling of the targets over the whole distance. The interesting finding was that for any target that could be reached within eight seconds, walking at a comfortable rate, with or without sight, the targets were reached with equal accuracy.

Again, we find that intending a future goal-state allocates the necessary resources before the first step is ever taken toward the goal. This is another concrete instance of an intention acting as a mathematical operator to set the teleonomic boundaries of an Ω -cell that are partitioned into an appropriate temporal sequence of teleomatic α -steps.

These examples, to our minds, provide strong evidence that the notion of an Ω -cell geometry for goal-directed behavior is more than a mere abstraction. In both of these cases, we see that the intent to act

toward some goal, acts as an exceptional boundary condition that harnesses the lawful relations and fetters the use of resources for the production of a goal-directed behavior. This exceptional boundary condition is, of course, the Ω -cell. It is an exceptional boundary condition relative to the ordinary boundary conditions of traditional physics because of its teleonomic nature. This teleonomic nature arises from the *anticipatory* role that perceptual information plays in parameterizing the allocation of the actor's resources. Let us consider next the anticipatory information that is available to an actor for the control of goal-directed behavior.

Anticipatory information

For an organism's intention to set the boundaries on the Ω -cell relevant to its goal, there must be available goal-specific information. Recall that goal-specific information co-implicates both manner of control of action and information about environmental targets. This co-implicative relationship between action and perception is the province of ecological psychology. Let us briefly survey what two decades of research in ecological psychology has concluded about the role of information in the control of action. To do so, we must first become acquainted with some fundamental concepts of this discipline.

An ecological system, or *ecosystem*, is a lawful coupling of an actor with an environment that supports goal-directed behaviors sufficient to sustain life and preserve fitness to reproduce (Gibson 1979). We take an ecosystem to be dually partitioned into affordances and effectivities (Shaw et al. 1982). An *affordance* is a property of the environment that potentially supports some goal-directed activity (such as graspable objects and surfaces that support locomotion), and, therefore, establishes an Ω -cell relative to that affordance goal. Indeed, we might say that the affordance partitioning of an eco-niche is the partitioning of the physical environment into Ω -cells. An *effectivity* is the means by which an organism actualizes an affordance as a potential behavioral goal (such as using the hand as a grasper or the legs to locomote). Therefore, the execution of an effectivity is tantamount to the controlled allocation of resources to realize the intended affordance goal. This is a partitioning of an Ω -cell into the sequence of α -steps.

Under this formulation, effectivities and affordances provide functional definitions for what is meant by an organism as an actor/

perceiver and its niche as that acted upon and perceived. Expressed in this way, affordances and effectivities imply Gibson's fundamental working hypothesis for ecological psychology, namely, his *principle of animal-environmental mutuality* (Gibson 1979). At the heart of Gibson's principle is the thesis that actors perceive the affordance properties of their environment from which they then choose what goal to pursue. Recent research supports this thesis (Warren 1984; Warren and Whang 1987; Mark 1987; Solomon and Turvey, 1988; Warren and Shaw 1985).

Not only is the environment perceived in terms of its affordance structure, the realizable goals, but there is also available to the actor information specifying the work to be done to achieve these goals. This means that information which is geometric or kinematic in character can somehow specify constraints on action involving kinetically defined variables. This function of informational constraints on action has been identified as the *KSD (kinematics-specifies-dynamics) principle* (Runeson and Frykholm 1981). Considerable research has revealed such informational constraints on actions across a broad range of environmental contexts. The KSD principle has been shown to hold for activities as diverse as walking (Runeson and Frykholm 1983; Todd 1982; Cutting et al. 1978) climbing stairs (Warren 1984), sitting in chairs (Mark 1987), lifting boxes (Runeson and Frykholm 1981), and wielding objects (Bingham 1987); and research on the inverse of the KSD principle where geometric properties are specified by dynamic exploration of a variety of objects (Solomon and Turvey 1988).

Thus, ample evidence supports the viability of the Ω -cell as a unit of analysis of ecological physics. That is, the effort to discover an ecological analogue to the energy conversion law is justified. Recall that a primary requirement of any physical geometry suitable to living systems must accommodate goal-directed behavior. It now seems reasonable to conclude that some of the qualitative intuitions that have inspired the enterprise of ecological psychology over the past several decades can be parametrized under a physical geometry that incorporates Ω -cell partitions. But this is only half of the story, for it addresses only the outer-tolerance limits on the resource allocation problem. As promised earlier, we must now seek the ecological analogue to Planck's energy distribution law. This entails discovering the quantal units of action by which an actor's steps toward the goal traverse the Ω -cell up to an α -tolerance limit.

Fuel coin analogy: Finding the common currency for energy and information

We can make clear our ecometric strategy for solving the dual aspects of the resource allocation problem illustrated in the experimental examples by considering an economic analogy. We need to show that when actions satisfy an intent, then information specifying target parameters and the energy expenditures dictated by the manner parameters are not only commensurate but must have the same basis of measure. That is, in 'seeing' *where* the goal is (target-parameters that set the Ω -cell), we must also 'see' *how* to attain it (specifies the manner-parameters that set the sequence of α -steps). Energy conversion from a perceptually specified goal-potential somehow must be made equivalent, in some common currency, to the energy distribution expended over the course of reaching that goal-state.

This means that there must always be equivalent but dual alternative descriptions of a successful goal-directed behavior. The first description, that of a physicist, would be in terms of the manner in which energy was expended to reach the goal. The second description, that of an ecological psychologist, would be in terms of the information employed to steer the course of the world-line to the goal. Each description gives you the path of α -steps that traverse the Ω -cell from the setting of the intention to its realization. An extremely simplified instance of what this involves is illustrated in the analogy below.

In some future city there is a delivery service that uses robotic vehicles to deliver goods anywhere within the city that a customer might desire. The goods are sometimes fragile and must, therefore, be transported over smooth terrain in a most careful manner. At other times goods to be delivered are more robust and thus may be jostled with impunity by jack-rabbit starts, hard braking, and sharp cornering over the roughest terrain. Thus, the customer selects not only a delivery target for the goods, but the manner by which they are delivered.

Each delivery vehicle is coin-operated in the literal sense that it runs off combustible fuel coins. Moreover, all of its driving functions, turning the engine on, setting the driving controls, idling, moving, steering, and braking also require *fuel-coins*. Absolutely nothing is free. This point can not be emphasized too strongly if one is to understand the economic cost of hiring the service to make a delivery.

There are no hidden costs. All costs fit into one of two major

categories: the cost of *assembling* the vehicle's start-state and the cost of *sustaining* its motion once started. The cost of assembling the start-state includes the cost of selecting a goal, that is, setting the vehicle's target and manner parameters, and the cost of initiating movement toward the goal. Here we assume that prior measurements have rendered all environmental exigencies part of the start-state assembly cost. The cost of sustaining the vehicle's movement includes the corrective adjustments that must be done along the way in order to reach the target in the manner preferred. Sustaining costs may be variable because some fuel is dissipated in overcoming mechanically produced friction built-up along the way. Other sustaining energy costs arise because of work that must be performed in overcoming unforeseen retarding forces or environmental thwarts to be circumvented. However, for the sake of simplicity, we shall assume that through a priori measurements by which target parameters were set, all nonfrictional sustaining costs were anticipated and assumed under the assembly cost. This is tantamount to assuming that the vehicle moves in a closed steady-state environment where there are no unexpected exigencies.

All of these costs sum to the total cost of filling the vehicle's tank with sufficient fuel to reach its goal, that is, to traverse the stipulated Ω -cell. Following Kugler and Turvey (1987), the amount of energy required for a given goal-directed activity, then, is given by the following equation:

$$E_{\text{total}} = E_{\text{assembly}} + E_{\text{sustain}}$$

The fuel-coins come in different denominations - their size being proportional to the amount of fuel that the vehicle burns as discrete energy squirts. That is, a fuel coin of denomination '10' delivers a discrete energy burst of twice the magnitude of a fuel coin of denomination '5', and so forth. The vehicle degrades the fuel coins in the order in which they are deposited. Thus manner is determined by both the number and denomination of the coins and the order in which they are deposited. For example, depositing a sequence of coins of denominations '2', '4', '8', and '16' will cause the vehicle to positively accelerate, while a '2', '2', '2' and '2' will cause the vehicle to maintain a steady-state velocity (assuming each subsequent deposit is made immediately after the previous coin is consumed).

The size of the fuel-coins range from large ones to very, very small ones, with larger denominations being exact integer multiples of the smaller coins. Indeed the largest fuel-coins exactly fill the vehicle's fuel tank. These coins contain sufficient energy to create a single 'bang' that will send the vehicle to the furthest destinations. Similarly, there are fuel-coins of intermediate denominations that will send the vehicles exactly to the end of any given route, so long as the distance to the target does not exceed the potential energy of the largest coin. Because of this fact, rather than each route being measured in centimeters or inches, they are measured in fuel-coin lengths. This is possible because each coin's diameter is exactly graded by its denomination, while the denomination numeral imprinted on each coin exactly corresponds to how many energy squirts it is worth in units of the smallest denomination.

The main points of the analogy that make contact with the conservation requirements of an ecological mechanics should not go unnoticed: The area of a fuel-coin of a given denomination, is an α -cell partition of an Ω -cell, and maps into a linear sequence of α -steps, or momentum 'squirts'. As will be discussed later, this mapping from an-area-to-a-line is a well-established mathematical procedure for reducing a higher dimensional form to a lower dimensional form. That is, a coin corresponds to an area proportional to the potential energy filling an Ω -cell and its denomination to the number of α -cells, whose conversion to kinetic energy are α -steps (momentum 'squirts') to the target. The smallest denomination plays a role analogous to Planck's quantum of action, h , but to a quantum of action at the ecological scale, while the largest denomination fuel-coin is analogous to Einstein's c^2 area of energy conversion but again scaled to the actor in question.

In summary, the main point to recognize is that the customer's selection of a delivery goal, like any actor's intention, entails that the manner and target parameters of that goal be expressible in the common dual vocabulary of a 'fuel coin' geometry. This is the case because the customer's choice of number, denomination, and the order of deposit precisely specify the distance the vehicle will travel and its manner of travel. Note that the prescription of the target parameters that define the Ω -cell and the α -steps that comprise a preferred manner can be described in commensurate terms of consumable resource units under this geometry. The trick demanded of the duality approach is seeing that both information and kinetic variables have a common

* KEY *

Assuming a
fixed structure

Use as way
to estimate
approx. time,
under Ω cells,
with a radius
in a lattice
over a path
assumed
constant velocity
(Ω cells)

basis in an intrinsic measure which yields an alternative metric description of energy in information terms. The rest of the paper attempts to make this claim plausible.

A mini-max duality as the basis for a new conservation

We show that because information variables and action variables are conjugate within a given Ω -cell, that is, when constrained by the same intention, then the sum of the information potential and action potential must be a fixed generalized quantity. This quantity is neither information nor energy alone but a generalized quantity to which both contribute complementary shares. This generalized quantity, called *the ecological action potential*, is *locally* although not absolutely conserved, in the sense of being indifferent to events across the full expanse of space-time. However, through extrapolation procedures to a living system's outer-most scale, it is tantalizing to conjecture that the ecological action potential for a given actor (or species of actor) would be conserved over a closed family of Ω -cells nested under some evolutionary super- Ω -cell. Such a super- Ω -cell might comprise a *ring of modes* – an auto-catalytic cyclic connection among goal-states, such as biological needs, that well-up on regular schedules; specific examples being goal-directed behaviors intended to satisfy hunger, fatigue, waste elimination, sexual urges, etc... (See Kugler and Turvey (1987: 89) for a thorough discussion of a ring of termite nest-building modes.)

Because fuel-coins are involved in both information detection and action control, they provide the dual basis of measurement for perception and action. On the one hand, they provide a measure for how perceptual information establishes the potential energy allocated to an Ω -cell. On the other hand, they provide a measure, in terms of an α -cell sequence, of the momenta associated with the corresponding α -steps to the goal. Finally, it cannot be emphasized too strongly that the conservation law in ecological mechanics only holds conditionally: so long as intention remains fixed on its selected goal, then the action potential remains constant within a given Ω -cell.

Fig. 8 is a further elaboration of fig. 7. Where fig. 7 introduces the Ω -cell specified by an intention, fig. 8 introduces the inner-scaling of the intention by interpolating the means for achieving the desired goal. These means comprise the sequence of α -steps over the α -cells that

'tile' a world-line through the Ω -cell in some preferred manner. An important result of this physical geometry is that as the actor approaches its goal, target-information is maximized while the energy expended to accomplish the elected manner of approach to the target is minimized. (Here we take *useful* information to be the complement of classical Shannon-type information – a measure of certainty or constraint. See below). The reverse is also true, namely, that the further an actor moves away from its intended goal, because of error, the more useful information about the target is decreased and the more useful work must be done. This *mini-max duality* guarantees the conjugacy of target parameters with manner parameters. (See Strang (1986) for a discussion of mini-max principles interpreted as mathematical dualities in the sense used here.)

Intuitively, this can be illustrated by the following example. If you wanted to hit a barn with a rock, the further you had to throw it the more work that would have to be done. Also, information for aiming the trajectory would be more problematic the further the distance; there would be fewer constraints and hence more possibility for misses. On the other hand, the closer you move toward the barn the less work must be done and the greater the certainty of hitting what you are aiming at. Finally, with your nose against the barn, minimal work for throwing the rock to hit it would have to be done, and the constraints on aiming, since the barn fills your field of vision, would be maximal.

This mini-max duality holds for all goal-directed behaviors – so long as the relevant Ω -cell is informationally prescribed and your manner of traversing it is guaranteed by a well-controlled sequence of α -steps; that is, α -steps whose underlying α -cells are perfectly interpolated to fill exactly the covering Ω -cell (fig. 8).

Fig. 9 shows that the total action potential to be converted to doing the work of goal-directed behavior can be actualized in various manners of control that correspond to different world-lines; and fig. 10 shows that for each manner of approach to a target there are different control 'decisions' to be made – each having a different information value. Thus the sum of all possible *manners-of-control*, over paths to a goal, is the total *information potential* available to the actor whose intention has selected that goal. This holds because they are world-line segments filling a given Ω -cell.

It is here with respect to manner of approach to a target that classical information measures of the Shannon-type play a limited role

the less
uncertainty
increases
certainty decreases
less work
more work
more perfect
information
less effort

more E. Part

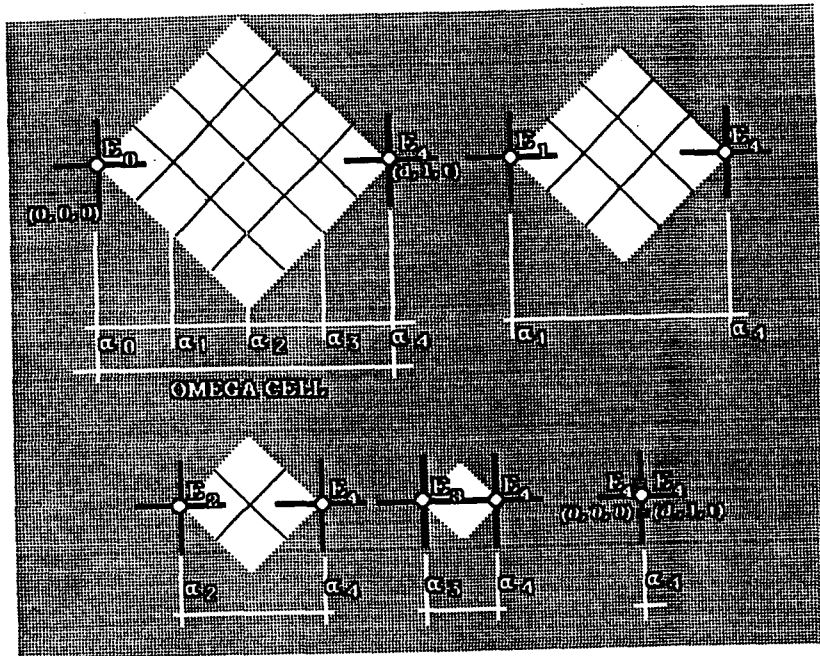
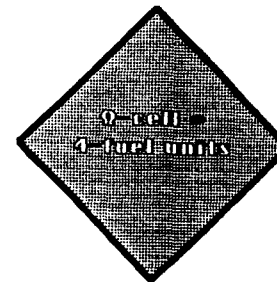


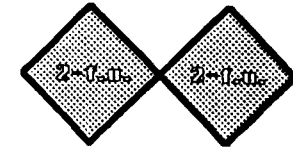
Fig. 8. Alpha (α) steps across an omega (Ω) cell toward a goal.

A goal-directed behavior is initiated when intent, guided by perceptual information and control preferences, allocates the *ecological action potential* anticipated. The 'ecological' action potential is both physical and psychological – consisting of both an *energy potential* and an *information potential* that must be specifically allocated for the intended goal-directed behavior. This behavior is defined kinematically as a temporal-backflow of information (from E_4 to E_0) from the target to the actor's current state. This anticipatory path (a world-line) is defined in terms of *target-parameters*: time-to-contact, direction-to-contact, and distance-to-contact. For a goal-directed action to be successful, then target information must conform to the intended manner in which energy is expended toward the goal. These kinetic control parameters, called *manner-parameters* include impulse-to-contact, torque-to-contact, and work-to-contact. These 'manner' parameters flow forward (from E_0 to E_4) toward the goal defining the energy that must be expended from the current position to the target in the prescribed manner if the goal is to be attained. Mathematically, the backflow on information and the forward flow of energy must follow dual world-lines that commute, that is, path integrals whose sum is zero. The cost of the energy to attain the intended goal (as measured in manner parameters) must be exactly inversely proportional to the cost of information to control the behavior (as measured in target parameters). In keeping with well-known theorems of linear programming, as useful energy is minimized, then useful information is maximized (mini-max duality theorem), and vice-versa. (See, e.g., Strang 1986: 695).

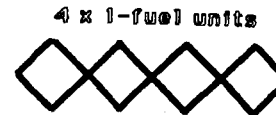
Mini-max duality of perception and action is guaranteed by the fact that all parameters are measured in the same units of potential energy (e.g., 'fuel coins'). From the initiation of the goal-directed behavior at α_0 , where the allocation of the anticipated action potential takes place, with corrective reallocations along the way, to the final goal-state α_4 , all of the ecological action potential is exactly expended. Otherwise there would be goal-undershoot or goal-overshoot, that is, E_4 is not perfectly reachable from E_0 . Because the mini-max duality holds between useful energy and useful information, then ecological action is conserved whenever a goal-directed behavior is successfully achieved. This is a consequence of the fact that $\Omega = \Sigma \alpha$. (See following text and figures for details.)



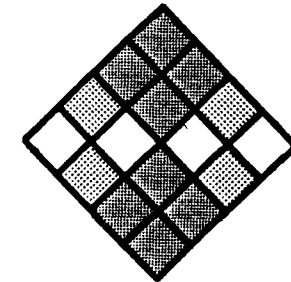
To traverse this Ω -cell in one α -step would require a single 4-unit fuel coin. The manner here corresponds to a single ballistic movement to the goal.



Here to traverse the Ω -cell still requires 4 fuel units. But the manner to do so takes two α -steps. Each of these α -steps requires a 2-unit fuel coin.



Here the manner of traversing the Ω -cell to the goal is being done in four α -steps. Here each α -step requires an energy "squirt" that consumes one α -cell worth a 1-unit fuel coin.



Note again that the number of fuel units to reach the goal across the Ω -cell is always equal. Hence manner parameters and target parameters are orthogonal and, therefore, provide the independent coordinates of a goal-directed behavior so long as they apply to the same Ω -cell.

Fig. 9. The common currency of manner and target parameters: α and Ω -limits rendered in fuel units.

The fuel bank for all behaviors is the total metabolic potential. The fuel bank is partitioned over time, by an 'intention' operator, into Ω -cells corresponding to its action goals. Each Ω -cell is an account (action potential) to be drawn upon in executing a goal-directed behavior. An Ω -cell is the spatio-temporal 'spread' of the Ω -fuel account. The Ω -cell is covered from boundary to boundary with α -cells, just as tiles cover a floor from wall to wall. The α -cells 'tiling' and Ω -cell are the checks that might be drawn against the Ω -cell fuel account. Cashing these checks provides the fuel-coins for the α -steps needed to cross the corresponding Ω -cell. Conservation of an actor's action potential is assured whenever cashing of the α -fuel checks is both sufficient to reach the goal and, in doing so, exactly exhausts the Ω -fuel account. If these books do not balance, then there will be control error producing a degree of goal-undershoot or goal-overshoot.

tion required would be (uncountably) infinite. For these reasons, a Shannon measure is inappropriate as an ecometric measure of perceptual information.

Ecological information avoids this infinite regress because perceptually informed intention is an operator that breaks the directional symmetry of the Besicovitch set at each α -step. The directional symmetry that is broken at this inner scale is broken by the self-symmetry of the outer-scale with the inner-scale under *fractal rescaling* (see below). Intention is the symmetry operation by which a goal-bias, originating in the Ω -cell, is passed down to the individual α -cells that sequentially link the actor's initial conditions to its stipulated final conditions. Thus directionality is hereditary over the α -partitioning of the Ω -cell. The extrapolative origins of that directionality, however, remain as mysterious to current theory as that of intention itself.

Let us summarize the demands for an ecological mechanics that we have discussed so far. The sum of the information (choice) potential, because of the mini-max duality, will always complement the physical (energy) action potential. This unity of the two complements is the ecological action potential. The ecological action potential is always conserved whenever an actor's intention is served and the information and energy balance so as to achieve the crossing of the designated Ω -cell in the preferred manner. It should be carefully noted, however, that this is a relative rather than an absolute conservation. Because the conservation of ecological action potential only holds with respect to a successful α -crossing of an intentionally closed Ω -cell, then this 'theorem' of ecological physics is more in keeping with Ehrenfest's theorem for adiabatic conditions that hold for quasi-closed mechanical systems. So long as the actor's intention is invariant and realistic (that is, so long as the actor's Ω -cell is an *adiabat*), then the conservation of the goal-directed system is as real, if not as general, as any other fundamental conservation law of physics. (See Kugler and Turvey (1987) for a detailed explanation of this theorem.)

Fractal rescaling: A self-symmetry that is symmetry-breaking

What kind of physical geometry is implied by the foregoing. Because α -cells must be perfectly interpolated under the intended Ω -cell, or conversely, the Ω -cell must be a perfect extrapolation from its α -cells, then we recognize that the inner- and outer-scaling of the tolerance

limits seem to fit perfectly. (Recall fig. 1.) A geometry for which this is so has the important feature of *self-similarity under scaling*. Such geometries are radically different from the geometries of the space-time continuum, such as Euclid's, Minkowski's, or even our dual-variant on Minkowski's space-time geometry. These geometries of the continuum are all deficient because they have no way to map a continuous area (potential energy with a quadratic formulation), such as an Ω -cell, into a discontinuous line of α -steps (momentum sequence with a linear formulation). That is to say, they can not really relate the energy conversion law, which requires n -dimensions, to the energy distribution law, which requires only $n - 1$ dimensions (where $n \rightarrow 2, 3, \text{ or } 4$).

Action geometries, being at the 'in-between' scale, must on the one hand be proportional to their *embedding space* (in our case a 2-dimensional space-time geometry), while on the other hand being proportional to a world-line as a lower-dimensional *embedded space*. The mathematical perplexity, then, for action geometries, is how they can bridge the outer-scale of higher dimensionality with an inner-scale having fewer dimensions. Hence we can only conclude that action geometries are degenerate because intention maps states of higher dimension (Ω -cells) into states of lower dimension (a sequence of α -steps). This is the bizarre but indispensable requirement for an ecometric solution to the resource allocation problem for goal-directed behavior. Luckily, there is a candidate geometry for accomplishing the ecometric mapping if only it can be given a proper physical/intentional interpretation. Fractal geometries and chaotic attractor dynamics based on them seem a hopeful choice. We will, however, address only the appropriateness of fractal geometry and leave their dynamic exploitation to a future paper.

The recursive nesting of smaller but similar figures under another by means of some generative rule defines a *fractal set*. The rule of nesting may be perfect or merely statistical. In the latter case noise is introduced that is itself self-similar over scales. Mandelbrot (1977) introduced the notion of a *generator* of a self-similar set which determines a set on nested similitudes by iterations of a basic pattern. The nestings need not be proper symmetries but may include improper symmetries, such as reflections, doublings, overlappings, separations, random seeds, and so forth. In the cases where the self-similarity of the set is not perfect but only approximate, then the generator must include the first iteration (Falconer 1985).

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For instance, fig. 11 shows one of the simplest self-similar sets – called the *Cantorian perfect set*. The generator rule for this set reduces the original pattern by 50% and then doubles it in the horizontal direction. Hence the height of the figure is reduced while its length remains the same. Whenever a figure changes faster in one dimension than it does in another, then after infinite iterations there is, at limit, the loss of a dimension. For instance, a square becomes a skinnier and skinnier rectangle until, at limit, it collapses upon a ‘thick’ line. That is, at limit an area can be made to approximate a line segment. (Later we shall have occasion to use this dimension-reducing procedure which the mathematical philosopher, Alfred North Whitehead, once dubbed ‘extensive abstraction’). Fig. 15 shows the first five iterations of a ‘fractal’ set defined by interpolating a reduced, reflected triangle (Ignore the caption for the moment).

Let us now apply the notion of fractal geometry to represent the ecometric approach to a physical geometry for ecological mechanics. Fig. 11 presents a candidate fractal geometry for a dual Minkowski-like event space–time – an Ω -cell. This Ω -cell is defined over two dimensions: *frequency* (the vertical dimension) and *time* (the horizontal dimension). This Ω -cell is set by two events – E_0 , the initiation of the intention, to E_1 , its goal to be satisfied. This is the outer-scale where the law of energy conversion holds. Interpolated between this Ω -cell and the line of discrete α -steps, E_0 to E_{256} , are rescaled, self-similar α -cell sequences, specific to the various uniform manners possible. Note that an indefinite number of nonuniform manners, such as accelerations and braking, can be represented by trajectories that range over the different frequencies of the intervening scales.

Although a fractal geometry is the most naturally constrained geometry yet considered, and so best able to accommodate goal-directed behaviors, it is also deficient when overidealized. One deficiency arises from selecting that subset of fractal geometries that exhibit perfect self-similarity under infinitely recursive rescaling. Such a property is too ideal because natural systems always and necessarily encounter fractal inhomogeneity at some inner-scale value. Ideal fractal geometries would encounter no symmetry-breaking and therefore be without tolerance limits; their interpolation and extrapolation would be without end. Therefore, a system with such ideal generative principles would imply perfect perceptual resolution and perfectly precise action control.

Real systems, as opposed to mathematically abstract ones, encounter

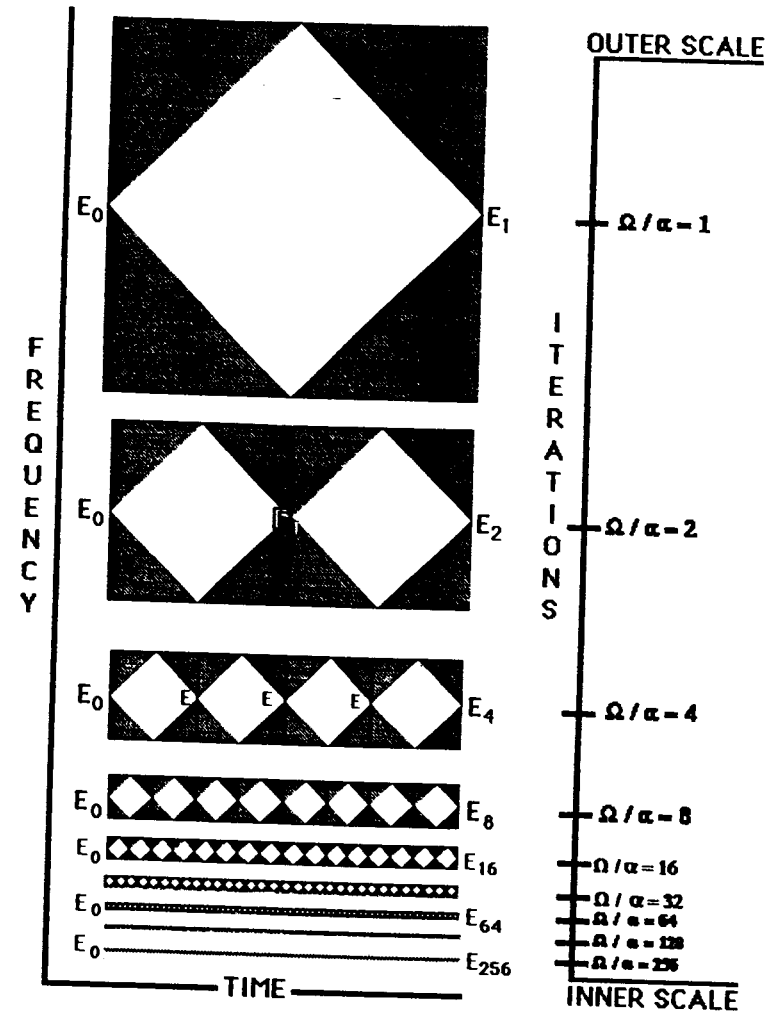


Fig. 11. Fractal rescaling of omega cell into alpha cell.

Fractal geometry assumes homogeneity over inner-rescaling, that is, $\Omega/\alpha = k$, where $k \rightarrow \infty$ as an ideal limit on interpolation; and over outer-rescaling, where $\Omega^*/\Omega = n$, for $\Omega^* > \Omega$ and $n \rightarrow \infty$ as an ideal limit on extrapolation. For instance, consider extrapolating outwardly from $E_0 - E_8$ to $E_0 - E_4$ or interpolating inwardly to $E_0 - E_{16}$.

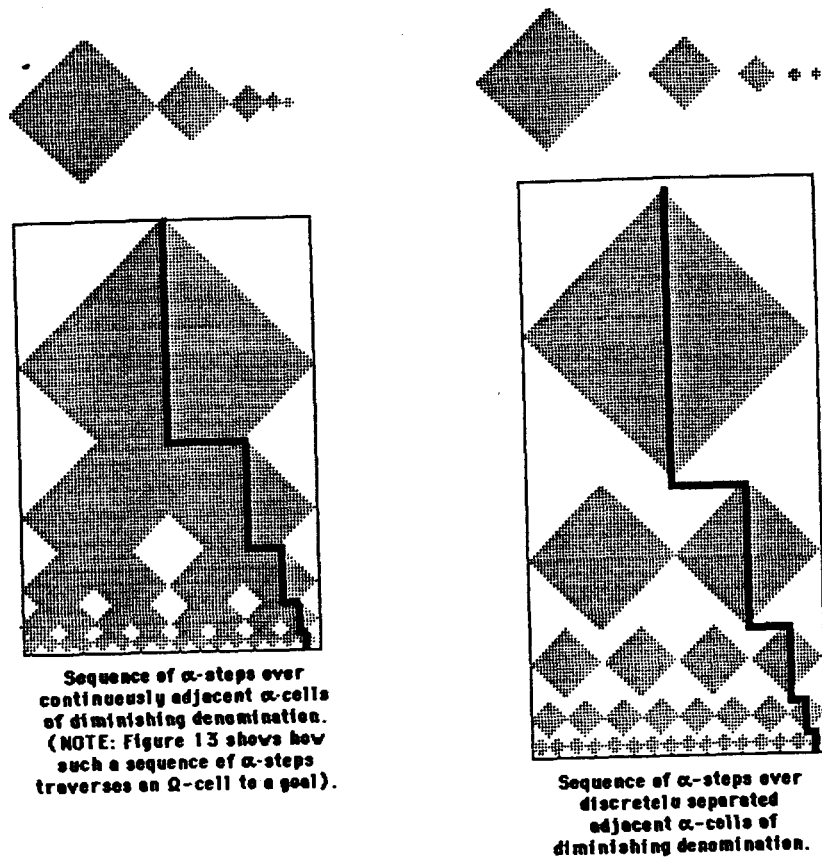


Fig. 12. Continuous versus intermittent alpha steps satisfying a controlled soft-collision.

In the two figures depicted above, we have two manners of control: a continuous decelerating approach to a goal (say, a hard surface to be softly touched by the forefinger) and a discretely decelerating approach to the same goal. In real systems that must be sustained by forcing functions because of dissipation of momentum due to friction, there can be no perfectly continuous control. Rather, all such systems are nonlinearly controlled by 'chattering' bursts of impulse forces when the potential energy of α -cells are converted into the kinetic energy of the associated α -steps. Hence the figure on the right is a more realistic fractal geometry. Notice that the Cantorian set upon which this discrete fractal geometry is based has voids, or 'cut-out' regions, separating the α -cells. This accounts for the discrete chatter of the control process. Between α -steps the system uses its momentum to 'coast' between bursts of quantal combustion. These voids are also the space-time regions wherein noise may enter into control. However, by a judicious adjustment of the 'cut-out' function, which controls the period between α -impulses, the noise might be filtered out so that manner of control is optimized for the goal-directed behavior.

perceptual 'noise' and control 'noise' because they are systems with finite rather than infinite limits on inner-scaling; they run into the equivalent of 'rounding errors' when exceeding their limits on resolution of target parameters and manner parameters. Figs. 12 and 13 illustrate this limitation. Notice that fig. 12 shows how the finite limit on fractal rescaling of physical systems (in this case a Macintosh SE computer) necessarily reveals increasing fractal inhomogeneity due to a breaking of self-similarity. This is an example of quantal 'noise'. In a living system this would set the limits on precise control or information resolution. In a fractal geometry quantal noise can be simulated by introducing finite recursion – an ad hoc restriction placed on the iterations allowed. Another way of introducing imperfection into the iterative self-similarity of a fractal geometry is by placing a random seed in its generator. The noise thus created shows itself as reduction in the degree of self-similarity over rescaling. Such noise shows a remarkable property: At each level of rescaling the noise reappears in the same proportion. That noise can itself exhibit self-similarity over rescaling from inner (microscopic) to outer (macroscopic) levels seems more a property of natural rather than artificial systems. One might expect, then, that natural systems could have evolved ways of coping with such noise where artificial systems could not.

Because of this property, fractal geometries show much promise for modeling goal-directed systems. Mandelbrot (1977) has suggested ways in which such self-similar noise can be eliminated by a judicious selection of 'cut-out' filters. Such filters may be constructed from Cantorian sets by empirically determining the intermittent frequencies at which noise occurs over fractal rescaling (fig. 14). We encourage researchers in the field of action theory to explore seriously this strategy. It holds out promise for a physical geometry which incorporates the intentional control of action as a lawful phenomenon. Let's explore the important role that cut-out functions might play in buttressing our argument for a conservation at the foundations of ecological mechanics.

Conservation of intention as a balancing of potentials

How efficiently can an empty area or an empty volume be filled, by adding tiles or packings, respectively, so as to leave as little interstitial

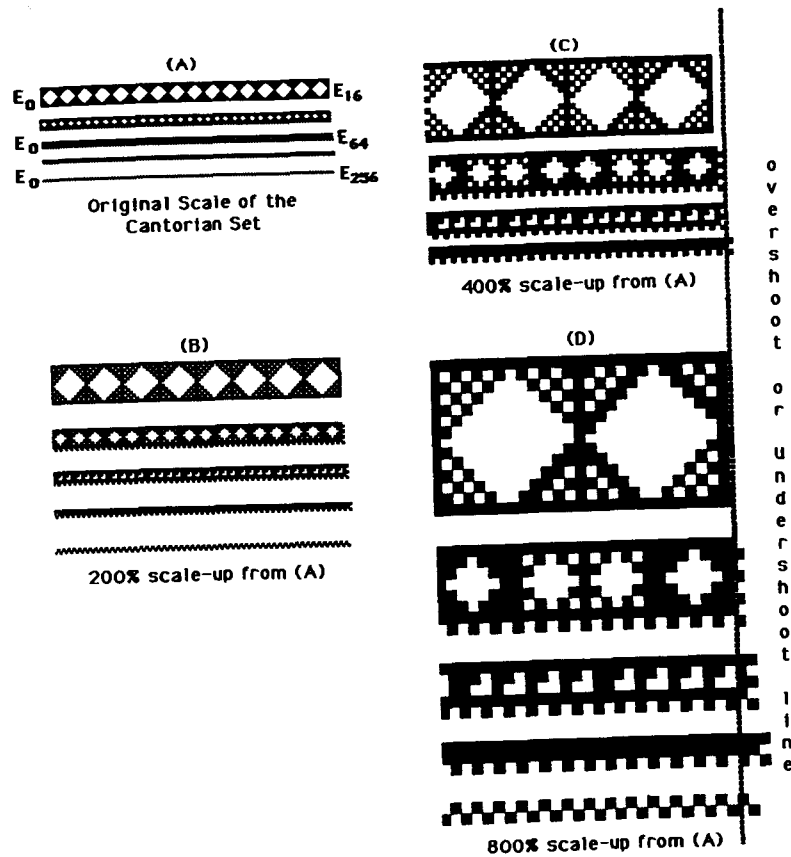


Fig. 13. Fractal inhomogeneity arising from quantal noise.

Fig. (A) shows iterations $E_0 - E_{256}$ (upper left) of the fractal geometry (the Cantorian set) depicted in fig. 11. Figs. (B)–(D) are increasing magnifications of the right-end portions of the fractal geometry. (By counting the number of 'diamond' regions, the area of fig. (A) magnified can be identified.) Two properties of the rescaling transformation are to be noted: The *first* property is that *fractal inhomogeneity arises from quantal noise*. Noise increases in direct proportion to the frequency. Ideally, with perfect self-similarity and infinite recursion over the rescaling iteration number, the frequency of the fractal sequence would increase without limit, while its length remained constant. In terms of the fuel-coin analogy, we would say that the larger denominations were being converted into smaller change without loss of total value, that is to say, the energy potential was not being short-changed, but conserved. However, because real systems are only finitely resolvable, then self-similarity has its limits; as inner-scaling increases, order merges into disorder. This is *quantal noise* (as opposed to random or thermal noise). In complex natural

void as possible? This is called *the minimal packing problem* (or *the minimal tiling problem*, dependent on dimensionality). A *dual* question is how efficiently can a filled area or a filled volume be emptied by subtracting tiles or packings, respectively, so as to leave as little filling as possible. This is called *the maximum cut-out problem*. Clearly, the minimal packing and the maximal cut-out problems are expressions of a *mini-max duality*. Earlier we claimed that this duality must hold for information and energy if a goal-directed behavior is to successfully traverse a given Ω -cell. (Recall fig. 8.) A still stronger claim is that this duality underlies the (local) conservation law upon which ecological mechanics rests. Consequently, it deserves formal clarification.

As discussed earlier, one might ask how many α -cells it takes to tile an Ω -cell if the energy potential is to be sufficient for an intended action (fig. 9). By analogy to the packing problem, one might ask whether the packing of an Ω -cell by α -cells is perfect. Or, are there interstices that are not filled by α -cells expended for control of action but by α -cells to be used for a different function. Let us designate as α_E -cells those α -cells representing the energy consumed in action. But detection of information to guide action is as important as energy converted directly to action organs. The *ecological action potential*

systems, however, new orders may arise under rescaling in a quasi-regular way – being interspersed between periods of intermittent noise. Here, for purposes of illustration, we have elected to address only a simple system.

A second property is that *the Cantorian mapping adopted for ecological mechanics expresses dimensional degeneracy* – a structure of a higher-dimension is collapsed onto a structure of lower dimension. If inner-scaling was perfectly recursive, then, (according to the Cantorian perfect set construction), the original, continuous Ω -cell would, at limit, converge onto a discrete line made-up of an infinite number of α -points. Fig. 11, depicts a 2-dimensional Ω -cell, an area, degenerating into a 1-dimensional sequence of discrete punctiform α -steps. Of course, in natural systems dimensional degeneracy is not perfect either but is only approximated. This must be so if the higher-dimensional energy conversion law (represented by the potential energy of a 2-dimensional Ω -cell in our illustration) is to be rendered commensurate with the energy distribution law (represented by a 1-dimensional sequence of α -steps, or momenta 'squirts', in our illustration).

Clearly, then we must expect all natural systems to have a finite, in-between, inner-scale limit on quantization which determines the smallest denomination for fuel 'coins'. The degenerate area will become a 'thick line', a world-line, consisting of a large but finite sequence of α -cells. The iterative scale value indexes an information measure of the behavior of the system which is dual to the manner-parameters. This information measure characterizes the twists and turns of the 'thick' world-line as the system chooses its path toward its goal. (See fig. 15 for further detail).

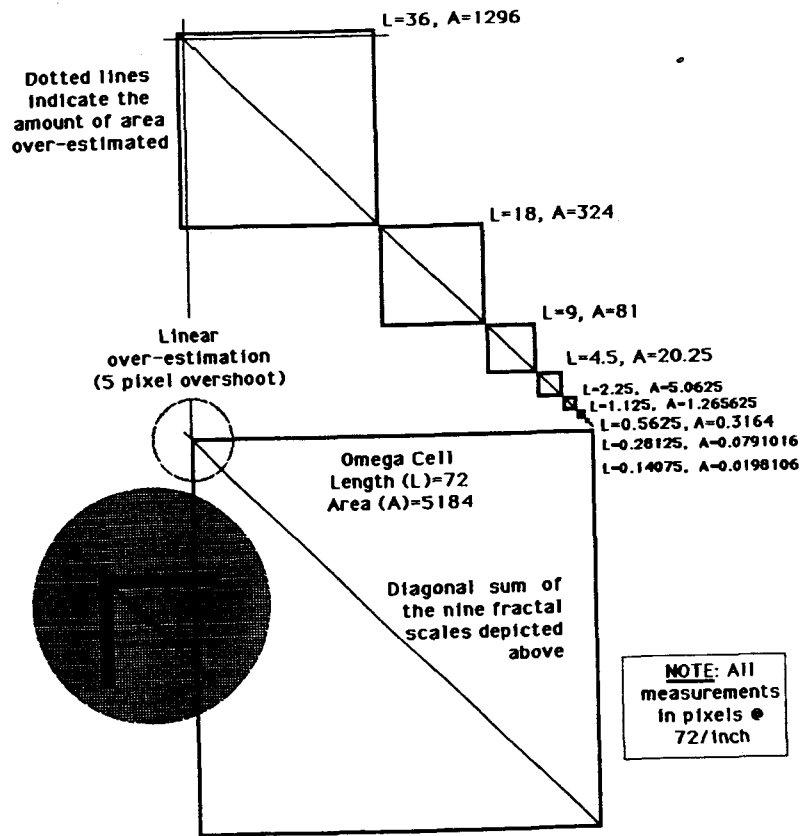


Fig. 14. Alpha limits on precision of fractal scaling.

Undershoot or overshoot errors occur whenever α -limits on fractal dimensions are surpassed during inner scaling. The interpolation procedure always encounters fractal inhomogeneity at some inner-scale because of the existence of a *greatest-lower-bound on quantization*. Consequently, one would expect optimal control where noise is minimal to exist at an inner-scale factor (an iteration number) just smaller than that scaling factor which encounters fractal inhomogeneity. This breaking of self-similarity of fractal scaling creates 'noisy' control. Such error means that information and energy are no longer perfect duals.

(Ω_{∞}) consists of both an energy potential ($E_{\text{pot}} = \sum \alpha_E$) and an information potential ($H_{\text{pot}} = \sum \alpha_H$); that is,

$$\Omega_{\text{oco}} = E_{\text{pot}} + H_{\text{pot}} = \sum \alpha_E + \sum \alpha_H.$$

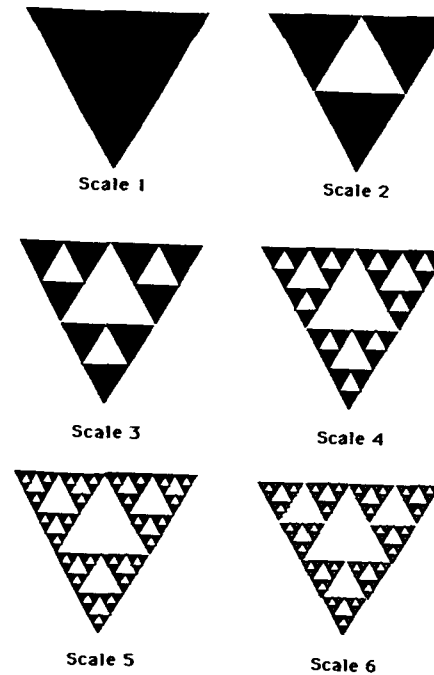


Fig. 15. Setting tolerance limits on information measures.

Some packing problems have solutions, like fractal geometries, that exploit *self-similarity*. A larger object is sometimes most closely packed by innumerable smaller versions of itself. For instance, a large square can be packed perfectly by nesting it with smaller squares (e.g., elements of a Cartesian grid packs the Euclidean plane perfectly). This is not true of all packing problems. A circular area has no self-similar solution; it is packed more closely by hexagons than by circles. In between packing problems admitting to perfect self-similar solutions and those with no self-similar solution, are cases where the self-similarity is imperfect. The closest packing of an equilateral triangle has an imperfect self-similar solution (Eggleston 1953). The best solution is to pack, repeatedly, each larger equilateral triangle with a smaller inverted equilateral triangle, whose sides are scaled down by one-half. Given a black equilateral triangle to be packed, notice the effects of this recursive rule: The black equilateral triangle (*Scale 1*) gets whiter and whiter (*Scale 2 - Scale 6*) as the packing increases.

As the packing frequency increases without limit, the triangle would look completely white. However, measure set theory tells us that even at limit, where the black area appears to have been converted to a white area, this is not mathematically true. For there would be an infinite set of infinitesimal black triangular points distributed over the original area. These comprise individual null areas that sum to zero. Hence at *Scale 1* the figure's triangular boundaries enclose a 2-dimensional set, while at *Scale k* $\rightarrow \infty$, the figure encloses a set of zero measure (called Sierpinski's 'gasket') (Sierpinski 1915). Analogously, in fig. 11, we saw how an area (an Ω -cell) lost a single dimension under the Cantorian mapping by converging on a sequence of discrete points (α -cells), whose individual lengths sum to zero, although (at limit) they are distributed 1:1 with the real line.

If the α_E -cell packing of the Ω -cell is not perfect, then what resides in the interstitial residuals? By the above equation, we see that within the Ω -cell, regions not filled by energy must be filled by information. For if we set $\Omega_{\text{eco}} = 1$, then $1 - E_{\text{pot}} = H_{\text{pot}}$. This conservation is graphically illustrated in fig. 15.

Assume that the Sierpinski gasket is one-half an Ω -cell, so that twice its area at *Scale 1* is the energy potential associated with a particular goal-directed action. Recall that it is a 'theorem' of ecological mechanics that an ecological action potential ($\Omega = 1$) (fig. 8) consists of both an energy potential (E_{pot}) and an information potential (H_{pot}) related by a mini-max duality. Also recall that no operation is without its fuel-coin (potential energy) charge - information detection (measurement) operations are no exception (Szilard 1925). We let the cost associated with each information detection operation (e.g., walking closer to get a better look or haptically exploring an object to determine its shape) be graded by fuel-coin denominations as before. By analogy, let the different denominations correspond to the frequency of the white triangles subtracted from the black triangular area and the number of informed action decisions correspond to the number of white triangles (the cut-out problem). Because they share the same common currency, the fuel-coin, then the information and energy must be measured in coins of a lowest denomination. To exploit fully our analogy, the minimal α_E can be thought of as a 'black' coin and the minimal α_H as a 'white' coin. (This poetic license is surely no more abstruse than the physicists giving their lowest denomination particles, quarks, the metaphorical properties of 'color', 'strangeness', and 'charm'.) Given that an actor succeeds in reaching a goal, then the mini-max duality locally sustains a conservation of the actor's intention over the Ω -cell if and only if the sum of the white coins (information cut-outs) perfectly complements the sum of the black coins (energy packings). This describes a stationary consequence of a successful balance between information detection and energy control - the closure of the perceiving - acting cycle in successfully traversing an Ω -cell without loss of control (too few white coins) nor loss of energy (too few black coins).

Thus, the finite limits on quantization is the finite scale of the Ω -cell as a kind of Sierpinski gasket. This means that the white triangles never cut-out all of the black area. If they did, the information measure for any size energy potential would be the same (infinite) - information

values with no boundary conditions. But if no black was cut-out at all, then we would have potential energy but no controlling boundary conditions on its distribution. Information and energy without the special boundary conditions, would be as theoretically useless to psychology as unmitigated singularities are to physics. Thus, just as Maxwell's demon must be banned from physics, so energy-free information detection operations (homunculi) must be banned from psychology. Information and energy potentials satisfy the mini-max duality but only within the ecometric bounds where a fixed intention operates - over an Ω -cell.

Summary and conclusions

In the course of this paper, the deficiencies of traditional physical geometries for modeling the actions of intentional systems have been examined. Both the space and time geometry of Newton and the space-time continuum geometry of Minkowski are overridealized and too under-constrained to be appropriate for action at the ecological scale. They share the common deficiency of treating all trajectories, whether mechanical motion or biological movement, as open-ended and continuous. We propose that this deficiency be remedied by moving to a modified *dual* Minkowski space-time geometry, where the cones of past and future paths are melded - a move excluded from traditional cause-and-effect geometries. By this ploy intention operates to partition cause-and-effect geometries into psychologically meaningful space-time regions, Ω -cells, whose boundaries encompass the informationally controlled actions of goal-directed behaviors. This move, therefore, sets the outer-scaling limits on action theory.

In addition, using Cantor's technique for fractalization, we showed how the inner-scaling limits, α -cells, follow from the recursive fractal interpolations of a given Ω -cell. However, because all natural systems have finite elements, fractal rescaling can not be infinitely recursive, but must bottom-out at that in-between scale where control-error (fractal noise) is below the tolerance-level for adaptive behavior.

Hence, by following Cantor's fractalization rule, we have a way to rescale continuous geometric objects so that their dimensionality is reduced. Moreover, by following it with finite recursion, we find that there are objects without integer dimensions but that fall between

higher and lower dimensions. These are Mandelbrot's fractals (Mandelbrot 1977). For example, the Fractal dimension of the Sierpinski gasket depicted is $D = \log 3 / \log 2 = 1.5849625$ – being more than one but less than two dimensions, while that for the Cantorian mapping of an Ω -cell onto α -cells with cut-outs of middle thirds is $D = \log 2 / \log 3 = 0.6309298$ – being less than 1 but more than 0-dimensions.

It will be an important task of ecological mechanics to discover the fractal dimension of the Ω -gaskets relevant to the support of given classes of goal-directed behaviors. This will be the local conservation number of the intention that must remain dynamically invariant over a space-time interval (a world-line) if the behavior is to reach the stipulated goal. If this can be done, then ecological mechanics will have an ecometric basis and the beginnings of a quantitative science.

This strategy of building ever more natural physical geometries is made possible by the lesson that all twentieth century geometers have learned from the great Riemann, who asserted, roughly, that the geometry of a space is no more, nor no less, than what you can put into it. The unusual structure for an ecological geometry arises because we have chosen to fill physical space-time with intentional behaviors. The next step, is to fill such a space with living systems that actually traverse the paths.

There can be no easy early assessment of the merits of a proposal for a new branch of science – least of all by its authors. Consequently, we have asked permission to conclude with a reviewer's comments that penetrate to the heart of the matter and might serve to focus the reader's critical acumen where it is most needed.

Epilogue

The thrust of the proposal is that information and energy can be unified under a general symmetry principle. The unification, however, is restricted to the Ω -cell. That is, the symmetry principle only applies within the context of an intentional constraint. As long as intention is sustained (or maintained), the symmetry that maps information into energy is valid – this is its relative nature. This stands in sharp contrast to classical unifying symmetry principles that have absolute or universal application. The integrity of the symmetry is based on the integrity of the intentional constraint – this intentional vessel is what distinguishes ecological mechanics from anything that remotely resembles classical, quantum, or relativity mechanics. If quantum mechanics is strange in terms of its symmetry operators, this

is even stranger. I think that this strangeness of an intentional operator will be the most difficult concept to sell, and yet its the very foundation for the whole scientific enterprise.

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MOVEMENT-PRODUCED INVARIANTS IN HAPTIC EXPLORATIONS: AN EXAMPLE OF A SELF-ORGANIZING, INFORMATION-DRIVEN, INTENTIONAL SYSTEM

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Solomon, H.Y., 1988. Movement-produced invariants in haptic explorations: An example of a self-organizing, information-driven, intentional system. *Human Movement Science* 7, 201-223.

Biological systems are the prototypes of self-organizing systems; systems that are self-starting, self-driving, adaptive systems. A self-driving, adaptive system is one whose evolutionary behavior is governed by the descriptions of the system, the initial conditions, and the constraints imposed by its environment. Basically, a self-driving, adaptive system is a dynamical system. This article is on a dynamic model of a task-specific, intelligent-mechanism of the haptic system. The mechanisms of interest is the hand and its appendages in the act of discerning the length of a visually occluded hand-held rod. Empirical observations showed that people are extremely adept in these tasks and the perceived lengths, considered as outputs of the mechanisms - hand-muscles-joints haptic subsystems, matched almost perfectly the actual lengths of the rods, particularly, when the rods were of uniform density and mass distribution. These observations pose, to the theoretician, the onerous task of discovering both the descriptions of the system as well as the inputs to the system. On the basis of several investigations, Solomon (Solomon and Turvey 1988) proposed a *Haptic Operator* model for the intelligent-mechanism of the haptic subsystem. The model characterizes the subsystem as a self-starting, self-driving, adaptive system whose outputs are only the invariant properties of its own dynamics. Because it is self-starting, the mechanism is identified as an intentional system. In this article, intentionality is simply labeled as a selection operator without further elaborations on the nature of the operation of selection. Because it is self-driving and adaptive, the mechanism is identified as an information-driven dynamical system. To underscore the information-driven character of biological systems, the article begins by distinguishing three kinds of dynamical systems: energy-driven, signal-driven, and information-driven systems. Then, the concepts of transformations and invariants are introduced to motivate the concept of dynamical invariants and the emergence of operators as representations of these dynamical properties. The article concludes by drawing the parallel between the invariants of a dynamical system and the invariants of the geometry of the system's dynamics and identifying information with the geometric/kinematic invariants of a dynamical system.

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