Computing like Nature
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Abstract
We address the framework within which Natural computation can be carried out, and
close that a birational ecosystemic hierarchical framework would provide for
computation which is closer to Nature. This presages a major philosophical change to the
way Science is carried out. A consequence is that all system properties appear as
intermediates between unattainable dimensional extremes, even existence itself. We note
that the Newtonian and Quantum mechanical paradigms make up a complementary pair.

Introduction
Does Nature compute? By matching computational models to Natural
phenomena we are
effectively saying yes. But we cannot know. All we can say is that this is how it looks. So how
can we compute like Nature? This is arguably what we are trying to do already. But is the
framework within which we compute sufficient? We would say no. We manage well enough for
systems which are close to linearity and equilibrium, but outside of that we quickly run into
difficulties. So what can we change? Quantum Mechanics (Liboff 2002) and ecosystemics
(Cronan 1996) have led the way – both of them insisting that we cannot operate in splendid
isolation. But we have not followed. Maybe we should. This is what we will address.

The ecosystemic paradigm consists of the complementary pair of organism and its ecosystem.
Critically, ‘the whole is not necessarily equal to the sum of the parts’, although the common
assumption that ‘the whole’ is automatically more than ‘the sum of the parts’ does not
necessarily hold (Koffka 1922). What we wish to do is to bring all of Science under a
generalized umbrella of entity and its ecosystem, and then characterize different types of entity
by their relationships with their relevant ecosystems. The most general way to do this is to
move the ecosystemic paradigm up to the level of its encompassing logic (Cottam and Ranson
2012), creating a complementary pair of conceivably different logics – one for the entity we are
focusing on; one for the ecosystem within which it exists – and providing for their quasi-
autonomous birational interaction.1

Much of what we will have to say addresses the manner in which we habitually describe, model
or point to the elemental ‘nuts and bolts’ of our surroundings, and whether our conventional
Scientific habits are sufficient, or even ‘fit for purpose’. In this, our birational approach is
closely related to the conventionally monorational discipline of semiotics (Chandler 2012;
Cottam et al. 2000a) – or the study of signs – and sign processes (semiosis), such as analogy,
metaphor, designation, signification, symbolism, indication and communication. In accordance
with linguistics, semiotics exposes the character and behavior of Natural objects and
phenomena in terms of syntactics – the relationships between signs themselves – semantics –

1 Throughout this paper we will use the term logic for the set of static operational rules which apply to a
specific entity in a particular context, and rationality for the context-dependent logically-determined
path through which the entity progresses, either as a consequence of its initial state or quasi-
autonomously towards a predetermined goal (this restriction to quasi-autonomy corresponds to a belief
that system (re)organization is always driven by contextual influences, and that there are no instances
of ‘pure’ self-organization).
the relationships between signs and their *denotata*, or ‘what they refer to’ – and *pragmatics* – the relationships between signs and the effects they have, or the contexts within which they are effective (Fisch 1986). The central thrust of our argumentation will particularly address the semantic relationships between models and their denotata, and the pragmatic relationships between denotata, or *denoted entities*, and their contexts, or *denoted ecosystems* in the terminology we will adopt.

Natural systems tend towards hierarchy. Multiple individual scales or levels are separated by complex regions whose character resembles a less-than-formal interpretation of ‘‘=’ in ‘1+2=3’ (Cottam and Ranson 2012). Inter-scale communication and scale isolation are both necessarily partial (Cottam et al. 2004b). Analogously to decision-making, such a *denoted entity* hierarchy is reductive towards localization. Somewhat surprisingly, the set of intervening complex regions make up a second, *denoted ecosystem* hierarchy, which is expansive – or ‘reductive’ in its own way – towards nonlocalization (Cottam et al. 1997). Each individual hierarchy embodies one of the two rationalities we created. At any extant scale there is a complementary pair of models of *denoted entity* and *denoted ecosystem* – one related to Newtonian representation, the other to quantal representation – both evaluated at that scale (Cottam et al. 2004a).

We believe that computation within this *birational* framework can be closer to Nature than conventional monorational approaches, most particularly for complex and living systems. We conclude that Scientific or philosophical investigations should *always* be formulated birationally, in a way which is related to the Western interpretation of *yin-yang* (Wong 1997) – as a complementary pair rather than an alternation of opposites.

A fascinating aspect of this birational approach is that representations and properties now always exist as intermediates between pairs of ideal extremes. Quantum logic no longer *replaces* Newtonian logic, it *complements* it (Cottam et al. 2008a), and it is then understandable that the measurement of a particle’s/quantal-wave-packet’s properties will indicate a *mixed* character (Mittelstaedt et al. 1987)! Science is often described as the child of Aristotelian pragmatism (2012), but this leaves no functional place for the abstraction of *models*. In a birational description, Science has two complementary aspects: the Aristotelian pragmatism of measurement and the Platonic abstraction of models. The complementary ecoystemic paradigm relates an individual to its global environment. This can be correlated, for example, with Turing’s advances in code-breaking (Erskine and Smith 2011), through the insistence on relating an individual coded message to the globality of its ‘environment’ of place, date, time, weather, … and proceeding by the elimination of consequently discovered contradictions. In a birational framework *existence itself* ‘becomes’ a derivative of localization and nonlocalization, and the entropy associated with living systems becomes a compromise between that of two complementary kinds of order.

The remainder of this paper is organized as follows. We begin by establishing the context within which we will proceed (‘Setting the Stage’). Our first focus will be on ‘size-dependent’ Natural properties (‘Scale in Nature’) and their organization in large Natural systems (‘Natural Hierarchy’). Next we will explore how these properties are interrelated (‘Inter-scale Interfacing’) and the nature of their classification (‘Digital versus Analogue’). This will lead us to considerations of system cohesion (‘Quasi-stability’). We will draw comparisons between Natural- and digital- information processing (‘Organisms and Computers’) and address the lack of pan-hierarchy in Nature (‘Hierarchy and Opportunism’). Our main focus will be on the
establishment of a general *entity-ecosystem* framework (‘Birational Complementarity’) and we will end with a reflection on its implications (‘Unavoidable Consequences and Conclusions’).

Contrary to its possible appearance, this approach is not at all anti-Scientific: it simply addresses an extension of the current Scientific point of view and of its inclusivity. It holds out the exciting prospect of conceivably bypassing the ‘red brick wall’ of complexity currently facing artificial intelligence and finally opening the way to developing *real* non-biological intelligent systems.

**Setting the Stage**

For us to address the current framework for computation we must first describe it. Scientific measurement and consideration take place in and around particular models, which are usually constructed in terms of a limited set of *independent parameters*, and are usually derived from previous conceptual forms through intuition or inspiration. The validity of a model is checked by comparing its predictions with *multi-parametric models* in other domains, resulting in an always provisional conclusion of acceptability or of definitive rejection. At any typical point in the temporal evolution of Science there is an overall coherence between models in different investigative domains: they will all be more or less related to a consistent grounding – the current paradigm, whether this be purely Scientific, or humanist, or religious in character.

At somewhat regular intervals (maybe about once a century?) there is an upheaval leading to change in the grounding paradigm, usually following a realization that information derived from the application of specific models to measurement data cannot be resolved within the current paradigm. After its three centuries of predominance, for example, the Newtonian paradigm began to be questioned around the turn of the 19th century following the discovery of what became known as the ‘ultraviolet catastrophe’ (Kuhn 1978). This led to the development of Quantum Mechanics in the first decades of the 20th century as a way of resolving the problem (Planck 1914).

However, a description of Scientific structure in terms of just model and paradigm does not tell the whole story. Both of these are subject to the all-encompassing constraints of logic. As a joint epistemological/ontological hierarchy, not only do punctual models exist within a current paradigm; a current paradigm itself exists within an over-arching logic structure. At this point we should emphasize that although human endeavor is most usually coupled to a single quasi-universal mono-logic, there is no reason why this should always be the case. Human language and discourse are so closely integrated with consequent mono-rationality that it is difficult to imagine any other way they could evolve. However, there is no obviously fundamental reason why a change in the grounding logic system should be philosophically excluded. Ecosystemics itself exhibits non-homogenous logic in the way that an individual species is related to the multiple other species of its environment. As John Kineman has pointed out2, if you remove the species of *bear* from an ecosystem, the remaining uninhabited niche or ‘*bear-hole*’ is not exactly equivalent to the missing species, as the bears’ absence immediately modifies relationships between all the other species present.

Our overall position is that now, at the beginning of the 21st century, a new ‘paradigm shift’ is necessary to resolve the apparent exclusion of *life* from biology and Science in general. Robert

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2 Private communication.
Rosen (1991) has pointed out that living systems survive and propagate through continuity in the relationships between their distinguishable parts, and not predominantly through the local characteristics of those parts themselves. The problem area is principally that of reductionism, whose over-application has led Rosen to describe biology as “the study of the dead”.

![Diagram of Logic Paradigm Model](image)

Since the nineteen sixties there has been a successful revolution in approaches to living Nature (Hagen 1992), through the development of a view relating organisms to their entire relevant environments – the development of ecosystems. Until now, however, this revolution has been confined to living Nature, leaving the ‘hard’ or ‘precise’ sciences of physics and chemistry...
untouched. We believe that it is now time for a new paradigmatic revolution which will extend the ecosystemic approach to all of Science in a way that makes it possible to integrate life into Science in general, while leaving the ‘exact’ sciences exact! The most obvious way to do this is to move the ecosystemic paradigm up from the paradigmatic level to that of logic itself, thus moving a large part of the paradigmatic complementary inter-dependence up to the logic level and creating a complementary ecosystemic pair of logics to replace conventional monorationality (Cottam et al. 2008a: see Figure 1(a) and Figure 1(b)).

Interestingly, this attributes very particular characteristics to the remaining parts of the original ecosystemic paradigm itself. Rather than remaining simply organism and ecosystem, these two now come to represent Newtonian and quantal mechanistic descriptions, respectively (Cottam and Ranson 2012: see Figure 1(c)). This places these two ostensibly discrete and independent paradigms in a complementary framework of relationships! It is comparatively easy to see why this should be the case. Newtonian Mechanics (NM) is based on the primacy of localization: it is specified in terms of precision and accuracy of local measurement. Quantum Mechanics (QM), on the other hand, is principally ‘nonlocal’ and probabilistic in its derivation and operation.

Stepping a little to one side for a moment, we should explain what we mean by nonlocal. Einstein’s (1920) relativistic arguments limit the speed of communication between any two real separated entities to the (measured) velocity of light – some 300 million meters per second. Nonlocality describes communication across space which transcends this limitation, which is nominally impossible in reality. However, Bennett et al. (1993) have proposed that instantaneous nonlocal communication of this kind is in fact possible, but that the decoding of such an ‘instantaneous’ message must rely in addition on a ‘real-time’ (or ‘real-speed’) communication between the two entities – thus eliminating the apparent ‘faster-than-light’ transmission of information.

The clearest example of the apparent difference between NM and QM descriptions and of their paradigmatic coupling is that of light. We can describe optical phenomena within both representational schemes: in the NM paradigm, light is represented as waves; in the QM paradigm, it is represented as particles. These two representations lie at opposite ends of a spectrum of size: waves’ only exist as spatial extensions; particles’ have no size at all. A fundamental aspect of NM is the unstated assumption that there is an instantaneous correlation between local and global properties. This apparently, and surprisingly, corresponds to the QM characteristic of nonlocality, but it is a false nonlocality which takes no account of relativistic communication limitation. Similarly, the QM description of light as localized photons, or particles, is a false description, as the probability wave of any ‘localized particle’ automatically spreads over the entire Universe! NM permits the existence of single-frequency optical waves, but any single frequency wave must also spread over the entire Universe, as a phase change at any location implies an analogous phase change at every other location. This injects nonlocality into NM! In a related manner, although photonic probability waves touch everywhere simultaneously, a photon’s position in ‘space-time’ can indeed be determined through attention.

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3 This scheme, referred to by Bennett et al. (1993) as ‘teleportation’ after the TV series Star Trek, does in fact work, and is in use for the uninterceptable transmission of coded information (e.g. Shields and Yuan 2007).

4 Note that for simplicity, we are describing the situation here only in terms of spatial extension: the word size we use can also refer to functional complication, or ‘extension’.
to its constraints, injecting localization into QM. We maintain that these two paradigms of NM and QM are opposite (complementary) ‘faces of the same coin’, and that they always coexist in any descriptive exercise.

This, then, is the first stage of our argument. Our intention is to replace conventional mono-rationality by a complementarily-coupled birational framework, derived from the ecosystemic paradigm, within which the conventional disciplines of Science – physics; chemistry; biology – may be successfully embedded without degrading their present performances. Conventional modeling relies heavily on reductionism in attempting to describe Natural phenomena, with the result that it cannot effectively deal with living organisms whose character is principally determined by their sub-systemic interrelationships. The primary aspect of our derived ecosystemic birational framework is the interrelationship between its constituent paradigms (Cottam et al. 2008b). This makes it an ideal support for representations of life itself, as an integral part of Nature rather than an uncommon emergence from it, to which end we reject any initial assumption of fundamental difference between organic and inorganic, between organisms and crystals, or between living and non-living. Consequently, a basic premise of our approach is that, in common with Nature itself, any distinction between living and non-living must automatically drop out of our subsequent modeling.

Scale in Nature
In general, Natural systems exhibit different scales. By scale, we mean ‘size’-related differences in properties. A distinction is frequently made between scale – in terms of spatially structural aspects – and level – in terms of functional complication or complexity. However, as will become clear, this distinction is irrelevant for the interpretation of Nature which we will present, and we will consequently use the words interchangeably where this is convenient. It is notable that although organisms often present a number of distinguishably different scales, inorganic entities exhibit few, and the differences between them, although observable, are less marked (Cottam and Saunders 1973). The number of scales exhibited by an organism ranges from a minimum for primitive forms, for example two for some slime molds/fungi5 (Railsback 2012), up to an apparently limiting upper number for mammals. Dinosaurs and mice exhibit similar extant scales, whose number depends on the framework within which it is established: for example ten (elementary particle, atom, molecule, molecule group, organelle, cell, tissue, organ, organ system, organism) from a simplified ‘Physics’ point of view, five (cell, tissue, organ, organ system, organism) in a simple biological framework (Westbrook 2000), or three (hadron, atom, cell, memon) in Jagers op Akkerhuis’s (2010) operator hierarchy.

In his booklet What is Life?: the Physical Aspect of the Living Cell Schrödinger (1944) attempted to couple the characteristics of organisms and crystals by introducing the idea of an ‘aperiodic crystal’ that contained genetic information in its configuration of covalent chemical bonds. This stimulated research which culminated in discovery of the character of DNA (Watson and Berry 2004). A closer connection between organisms and crystals can be found in the structure of some fundamental biochemicals, for example the lipid pdmpg, which exhibits an almost crystalline regularity in its structure (see Figure 2). In any case, the major defining

5 Note that we attribute two scales to an entity with a single level of internal structure and an overall outward appearance (Cottam et al. 2000b).
characteristic of any scale\textsuperscript{6} system is the nature and quantity of information which is transferred between its different scales. In an organism the informational differences between scales can be enormous; in a crystal they are minimal (Cottam and Saunders 1973).

A vital aspect of any multi-scaled system is the difficulty of establishing a conventional externalized 3\textsuperscript{rd} person point of view or description. If there were no difference in properties between the different scales, then

1. it would be very easy to formulate a 3\textsuperscript{rd} person description, because
2. in that case there would not be any different scales at all,

which is virtually the case for a crystal, where macro forms follow on almost directly from microscopic atomic arrangements. Such is far from the case for organisms, where cross-scale informational differences can be extreme. Consequently, a different 1\textsuperscript{st} person description will be associated (at least) with each scale, and it will be impossible to generate an accurate 3\textsuperscript{rd} person ‘summation’ of these from an external viewpoint. If for no other reason, this makes it impossible to ‘understand’ another person’s mind (Cottam et al. 2008b)!

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{The almost crystalline structure of the lipid pdmpg.}
\end{figure}

\textbf{Natural Hierarchy}

Having introduced the presence of an organism’s different organizational scales, we must now reflect on how they are coupled together to present the unified appearance we perceive as a 3\textsuperscript{rd} person interpretation from outside\textsuperscript{7}. Natural systems tend towards hierarchy (Salthe 1993). This character of ‘hierarchy’ is closely related to the correspondingly named structure which is applied to business enterprises, where different levels of organization – such as chief executive (CE), top-level managers, middle management, foremen and worker-drones – are coupled together to provide a hopefully efficient coordinated activity. In a Natural context the overall organization is much more coherent and self-consistent than in a business – from both top-down and bottom-up perspectives – and there is no single predominant level which is comparable to a business’s CE. Consequently, we will always portray a hierarchy ‘on its side’, with the ‘top’

\begin{itemize}
  \item[\textsuperscript{6}] Note that we will use the word \textit{scale} intentionally as an adjective in place of the more grammatically correct \textit{scalar}, to avoid confusion between references to the scale phenomena we are describing and the mathematical entity of a \textit{scalar} (as a noun).
  \item[\textsuperscript{7}] Ultimately, such a reflection results in the expression of a concept referred to as \textit{hyperscale}, but for the sake of brevity we will not address this aspect here, as it is not directly relevant to our argument. An extensive description of hyperscale and its implications may be found in a number of previous publications (e.g. Cottam et al. 2004a, 2006, 2008a, 2008b).  
\end{itemize}
(i.e. the equivalent of CE) at the right hand side. Salthe (1985, 1993, 2012) has extensively described the properties of hierarchy in Nature. However, he restricts the term hierarchy to two forms: the scale (or compositional) hierarchy and the specification (or subsumption) hierarchy. We consider that a third form – the model hierarchy – is most suitable for describing the properties of Natural systems. An example of a Natural model hierarchy could be that of a tree (see Figure 3(a)), where the differently scaled models are {a tree described in terms of atoms}, {a tree described in terms of molecules}, {a tree described in terms of cells}, … up to {a tree described in terms of branches}, {a tree as itself – a tree}. Our generalized portrayal of a Natural model hierarchy is presented in Figure 3(b) for this same example of a tree, where each vertical line represents a differently scaled multi-parametric model in terms of the quantity of information needed to describe it (which would, of course, be far more extensive for the population of worker-drones than for the CE; and more extensive for ‘a tree as atoms’ than for ‘the tree as itself’).

![Figure 3: (a) A tree, as a simple example of a multi-scale model hierarchy; (b) The general representation of a Natural model hierarchy for this same example of a tree. Each vertical line represents a differently scaled model in terms of the quantity of information needed to describe it. The inter-scale regions indicated are multiply fractal and complex.](image)

It will be evident from Figure 3 and from the description we have given that the character, or at least the quantity of information at each organizational scale, will be different. This is a major problem: how can adjacent but dissimilar multi-parametric scales be self-consistently
correlated? Surprisingly, we encounter the same difficulty even with a simple arithmetic equation such as 1+2 = 3, where we lose information on going from left to right, as we drop one of the 2 digits we started with (i.e. from ‘1+2’ to ‘3’), and we consequently lose its degrees of freedom\(^8\). If we try subsequently to return towards the left hand side from the single ‘3’, it will become obvious that we have no way at all of knowing whether we started initially on the left with 3, or 1+2, or 2+1, or even 1+1+1!

In general, therefore, if we ‘travel’ from a lower extensively detailed multi-parametric scale to a higher one whose description requires fewer parameters, we must remember that it will no longer be possible from there to accurately determine the characteristics of the lower scale. The only solution to this problem in a general Natural setting is to relax any prerequisite for absolute informational accuracy. As a consequence, individual scales will be partially isolated from each other. However, they will still be partially inter-communicating, so that approximately complete and apparently self-consistent correlation can be carried out between them. This is a fundamental property of a Natural hierarchy: individual scales are partially isolated from each other, and only partially communicating with each other.

**Inter-scale Interfacing**

The regions between adjacent scales in both Figures 3(a) and 3(b) are virtually impossible to model, even by some kind of extremely simplified approximation. The ‘=’ we are used to encounter in expressions such as ‘1+2 = 3’ is logically defined in its arithmetic context as a statement that the left and right sides of the ‘equation’ are indistinguishable. This is clearly not the case: the character string ‘1+2’ is easily distinguishable from the string ‘3’. This is one of the drawbacks of conventional mathematics in its application to real-world problems: even though extensively useful, it is far too short-sighted in its formality to comprehensively represent even the simplest of circumstances. If we try blindly to rely on ‘1+2 = 3’ to represent a left-to-right summation of apples, we can end up on the right with one very big apple! Even so, will this super-apple be equivalent to ‘1+2’ apples in terms of width, or of weight, or of color, or of taste? We have no way of knowing. From a wider perspective which takes account of unspecified properties, ‘1+2 = 3’ is primarily a hierarchical relationship: the two sides of the ‘equation’ characterize different scales. The only way we can rely on this kind of equation is to provisionally close our eyes to reality and trust the abstract formal nature of mathematical definitions. Then, in some but not all contexts, we will be successful: 1 apple + 2 apples can happily result in the 3 apples we would like, for example – if we disregard disturbing properties such as degrees of freedom.

The coordinating relationship between any pair of adjacent scales of a real Natural entity, therefore, will be very different from the abstract equivalence of ‘=’. Communication between the two must be bi-directional, but this bi-directionality will be unavoidably asymmetrical. It must take account of differences in properties between the two scales; most particularly those which apparently disappear or emerge during passage through the intervening region. Above all, it must be aware of the entity’s more global context, which it must be able to adapt to. The resulting overall relationships which characterize the inter-scale regions, therefore, must be

\(^8\) The number of degrees of freedom of a system or of one of its elements can be defined as the minimum number of coordinates which are required to specify its state. If we describe the state of a non-rotating element in three-dimensional space, for example, it will possess three translational degrees of freedom.
appropriately applicable in any conceivable local circumstances. This makes these regions complex in the manner described by Robert Rosen (1991):

“A system is simple if all of its models are simulable. A system that is not simple, and that accordingly must have a nonsimulable model, is complex.”

Consequently, the only way to completely formally represent one of our complex inter-scale regions would be by employing an infinite number of models, which seems somewhat impractical! It is also impossible to manageably digitize these inter-scale regions, as completely accurate conversion would require an infinite number of digital bits. This makes the inter-scale regions archetypically analogue9 in character (Cottam et al. 2005).

In reality, the situation is even far less obvious than it at first appears. If we examine either Figure 3(a) or 3(b) of our example of a tree, the extreme right hand side of the illustration corresponds to a digitized representation of whether the tree exists or not: the tree’s ‘reality’ is modeled as true or false, equivalently to the ‘1’ or ‘0’ of conventional computing notation. If we now move progressively towards the left of Figure 3(a) or 3(b), we pass through a scaled sequence of multi-parametric representations, which through {a tree described in terms of branches}, {a tree described in terms of cells}, {a tree described in terms of molecules}, {a tree described in terms of atoms} approaches more and more closely a detailed analogue description of the tree10. So, the extreme right hand side of Figures 3(a) and 3(b) corresponds to a digital representation of the tree; the extreme left hand side corresponds to an analogue representation. This illustrates the principal character of a multi-scale Natural hierarchy: it provides an interface between analogue and digital representations (Langloh et al. 1993)! We submit that Natural hierarchical interfacing of this kind constitutes the defining feature of our Universe. There are far-reaching consequences of this proposed introduction – most particularly with respect to the historical evolution of the Universe.

**Digital versus Analogue**

Conventional interpretation depicts the origin of the Universe as a uniform, undifferentiated state of infinite entropy which precedes space and time (Drees 1990). Following the Big Bang, later stages of Universal expansion develop differentiation into a multiplicity of more ordered and consequently less communicating entities, whose configuration in the absence of life progressively decays through time towards the uniform entropy of ‘heat death’ (e.g. Adams and Laughlin 1997). In its most complete form, Natural hierarchy delivers the temporal interface between the infinite analogue entropy of the Big Bang and the digital character of evolved multiple differentiations. To be consistent, therefore, we should not only always resort to our generalized representation to clarify the properties of any multi-scaled entity or phenomenon; we should also ‘insert’ it into any context where analogue and digitized structures or representations are physically or functionally adjacent.

Figure 4 indicates the consequences of inserting our entire hierarchy between any digital-analogue adjacency in an extended rendering of Figure 3(b). Between each pair of multi-

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9 Note that to avoid confusion we will consistently use the spelling ‘analogue’ here, implying, as we logically should, that the analog referred to in digital information processing systems and the analogue referred to in inter-dimensional comparison are directly related, if not precisely the same.

10 We are aware that we have here avoided any discussion of the potential analogue or digital nature of space-time itself. We do not believe, maybe surprisingly at this point, that such a debate would radically alter the basic ideas we present here. Further reading of our argument will support this belief.
parametric (and therefore digitized) model scales lie complex (analogue) regions: we must insert \textit{at least} a version of our entire hierarchy between the scales at every stage\textsuperscript{11}, as shown in Figure 4. But this will not be enough. We have now, in each case, implanted between \textit{analogue} and \textit{digital} a set of digitized sub-scales, and are faced with the frightening prospect that we should \textit{again insert at least} a version of the entire hierarchy \textit{between these… and so on, ad infinitum!} We end up with an infinite sequence of scales, sub-scales, sub-sub scales, sub-sub-sub-scales,… whose repetition towards smaller and smaller size resembles the \textit{self-similarity} of fractals (Mandelbrot 2004). This progressive finer and finer accumulation of ‘detail repeating itself’ not only makes the inter-scale regions infinitely (digitally) fractal, but also makes them digital reproductions, or \textit{digital facsimiles}, of analogue complexity. It unavoidably, and somewhat confusingly, makes the \textit{entire} Natural hierarchy we are describing a primarily \textit{digital facsimile} of what initially appeared to be a purely analogue view of our surroundings!

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure4.png}
\caption{the consequences of inserting our entire hierarchy between any digital-analogue adjacency.}
\end{figure}

\textbf{Quasi-stability}

The picture we now have of the constitution of a Naturally-hierarchical entity or system is one of multiple constituent elements which are distributed throughout multiple dissimilar scales of organization. A degree of cohesion between these different elements is necessary to prevent the entity or system fragmenting into a disorganized collection of lower level components (Collier 1999), and this cohesion must be communicated throughout the entity or system, at the very least at its lowest organizational level. For an organism, for example, there must be enough communicated cohesion at the level of the individual cells. If the organism expands beyond a particular size the local communicational overhead required to maintain cohesion will become excessive, and the only alternative to fragmentation is to reorganize in a way that reduces this local overhead (Cottam et al. 2008b). The generation of a new higher scale can achieve this by replacing a multiplicity of local communications by a reduced number of higher-level long range ones. More correctly, any reconfiguration to prioritize long range communication will only take place \textit{if} it will result in lower overall communicational overhead. This is a Natural analogue of the technique used in large scale computer chip manufacture of grouping communications between different regions of the chip to increase speed of operation and save energy (Hardesty 2012).

\textsuperscript{11} We will refer later to the presence in this sentence of the phrase ‘at least’.

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If our represented multi-scale Natural entity or system is to be at least provisionally stable it must be able to inter-correlate its different partially-isolated scales effectively – most particularly and most consistently at its lowest levels of organization. The solution to this conundrum, however, is comparatively simple. The greater the stability of the entire entity or system, the greater the proportion of information crossing between scales which is quasi-static and structure-supporting in character. This is very clear in the case of the long-term stability of an inorganic crystal (e.g. gallium arsenide: Cottam and Saunders 1973), where nearly all of the inter-scale transfer of information is structural, and information content is virtually identical across scales. It must, however, also be the case for an organism, as a means of maintaining its quasi-stability. We can conceptually split any inter-scale information transfer into two functionally-different parts. One of these is the quasi-static structure-supporting information we have already referred to; the other is any remaining non-quasi-static information, which although being unexceptional from the ‘point of view’ of the ‘transmitting’ scale, will be novel to the ‘receiving’ scale. Although neither of these two parts can be rigidly defined, we find ourselves once more in a domain where Aristotelian pragmatism lies between Platonic dimensional extremes: the biological reality of an organism’s quasi-stability lies in the middle ground between the two extremes of stability-supporting static information and stability-weakening novel information.

Organisms and Computers

In his book Life Itself: a Comprehensive Inquiry into the Nature, Origin, and Fabrication of Life, Robert Rosen (1991) has extensively addressed the criteria for existence of a living organism in terms of its indispensable internalization of Aristotle’s (2012) efficient cause, or ‘means of creation or construction’. His ultimate depiction is of an integrated graph of feedback or ‘looping-back’ processes, each representing one of an organism’s internal functions of Metabolism, Repair and reproduction – his (M,R)-system. Although open to a degree of criticism (Cottam et al. 2007) his graph confirms, unsurprisingly but somewhat realistically, that an organism is indeed only quasi-stable, corresponding to our conclusions in terms of cross-scale information transport. Rosen (1991) has suggested in reference to his book’s figure [10C.6] that:

“Any material system possessing such a graph as a relational model (i.e. which realizes that graph) is accordingly an organism. From our present perspective, we can see that [10C.6] is not the only graph that satisfies our conditions regarding entailments; there are many others. A material realization of any of them would likewise, to that extent, constitute an organism.”

The Natural model hierarchy we are describing is capable of reproducing at least the relational functionality of Rosen’s figure [10C.6], but it also enables us to progress much farther than Rosen’s (M,R)-system implies (Cottam et al. 2007). From the character of inorganic crystals we have referred to, and the conceptual split we have proposed between stability-supporting static information and stability-weakening novel information, it is clear that the former quasi-static cross-scalar informational relationships specify nothing other than a non-living system, while the latter novel or closely scale-related informational relationships are what make an organism alive!

The last few decades have seen a wide-ranging growth of research into artificial intelligence, artificial life and artificial consciousness – all three of these addressing the essential nature of
living organisms through the medium of digital computation. It is important, however, to note that although digital computers realize enormous benefits in some areas of information processing, they suffer from a number of critical disadvantages when compared to an organism. While the evolution of digital systems has followed a path which is conceptually in parallel to that of Natural organisms (Golshan 2007), they implement radically different logical structures, and this makes for a fundamental dissimilarity in the ways they can operate and in what they can achieve. Conventional digital computers consist of a (very) large array of simple Boolean logic gates. These are connected together in a complicated manner to provide the extensive abstract functionality to which we are now accustomed. However, each gate is a physically real entity, and takes a certain period of time to provide an output that correctly corresponds to its current inputs. To avoid consequent logical errors, a repetitive clock signal tells all of the gates to wait for a predefined ‘settling time’ before passing on their outputs to subsequent gate inputs.

It is most instructive to describe the computer clock signal with respect to a completely different characteristic: it completely isolates each gate from all of the others, except in the ways that the computer was conceived or programmed. Consequently, a digital computer is only capable of exhibiting local control or phenomena: it is incapable of generating or accessing any global properties. This, then, makes it impossible to generate in a digital computer any phenomenon which depends on globally-coupled properties, such as intelligence, life or consciousness (Cottam and Ranson 2012). A further disadvantage of Boolean implementation is that every gate in a digital computer is at the same non-hierarchical level (Cottam et al. 2004a). This means that the bigger the computer’s gate network, the slower the computer will perform (thus the race during the last few decades to increase computer clock-signal frequency or speed). A Naturally-hierarchical multi-scale organism functions in a completely different manner. The partial isolation of its scales means that most of its information processing is being carried out at its lowest scales, and the highest, most abstract scales can operate in real time quasi-independently of the lower ones. This is an enormous advantage to an organism, as it means that its large complicated and complex system can react comparatively rapidly to threatening external stimuli (Cottam and Ranson 2012).

Hierarchy and Opportunism

Following on from our submission that Natural systems tend towards hierarchy it might be expected that we would find hierarchical organization literally everywhere. But such is not the case, and we must explain why. It should be noted that we have only submitted that Natural systems tend towards hierarchy – not that they necessarily achieve it. To see why this is so we must look at the implications of Evolution.

Darwin’s (1859) 19th century depiction of the Evolution of organisms specified the three essential features of variation, reproduction and selection. Conventionally, his variation is associated with DNA mutation, his reproduction corresponds to our usual description of reproduction, and his selection is carried out by the survival or death of members of a species through environmental influences, cooperation or competition. We consider that these three essential features are the result of the evolution of Evolution itself, from a simple integral form more reminiscent of that normally associated with simple chemical interactions to a later ‘crystallization’ corresponding to Darwin’s differentiated description. This then suggests a continuity of evolution from the Big Bang up to the present day, during which every development of our Natural environment has been subject to prior influence.
Evolution is opportunistic, if nothing else. Nature has not been created ‘in one go’: it has evolved from state, to state, to state on the basis of what went before. This means that the characteristics which we observe today do not necessarily correspond to a ‘rational’ construction. This is very clear from the current physiognomies of organisms. Referring to the progressive evolution of physical characteristics, Sigmund (1993) has pointed out that:

“What serves for thermoregulation is re-adapted for gliding; what was part of the jaw becomes a sound receiver; guts are used as lungs and fins turn into shovels. Whatever happens to be at hand is made use of.”

This is the real character of Evolution. We ourselves, for example, have a backbone which originally evolved to support our hanging internal organs while we moved around on four limbs. Fortunately, not all the consequences of Evolution are disadvantageous. Much of evolution can be associated with the distribution or exchange of *autonomies* between members of a species, internal scales of an organism, or even whole parts of an organism. Collier (1999) has provided a beautiful example of this kind of relationship, in his suggestion that our brains have gained gain informational autonomy by ceding supportive biological autonomy to our bodies.

In an opportunistic Evolutionary environment, we cannot expect that current Natural states or organisms will always correspond to the tendency towards hierarchy we have suggested. Even so, much of our surroundings *does* correspond to a hierarchical model. For example, there is even evidence that parts of our brains operate hierarchically (e.g. Zhuo et al. 2001), while other parts do not (e.g. Rossion et al. 2010).

**Birational Complementarity**

We now come to the central issue we wish to address. The study of ecosystemics leads us to the assertion that *birational* concepts are more general than conventional *monorational* approaches in their applicability to the disciplines of physics, chemistry and biology. We consider that Science should be reformulated to take account of what Nils Bohr believed to be an all-pervasive complementarity (Katsumori 2011). We do not imagine, however, that a *binary* ecosystemic complementarity is the ultimate scenario towards which we are heading: Nature operates through multiple coincident complementarities, and in moving towards a binary representation we are simply taking the first step towards a hoped-for future intellectual multi-complementarity more closely related to the informational integration of consciousness (Tononi 2004; Schroeder 2012; Cottam and Ranson 2012).

Figure 3(b) portrays the general representation of a Natural scale hierarchy, with discrete (digitized) scale models separated by (analogue) complex regions. Figure 4 does not in any way contradict this portrayal; it merely catalogues more clearly the complexity of the inter-scale regions. However, we now note an entirely unexpected feature of Natural hierarchy. Close attention to the comprehensive assembly of relationships between the individual scales, the individual complex regions and the unified nature of the denoted entity indicates that the set of inter-scale complex regions forms a previously unnoticed *second* hierarchy, whose different ‘scales’ are interleaved with those of the initial one (Figure 5) (Cottam and Ranson 2012).

An apparent contradiction must now be resolved. We have suggested that the inter-scale complex regions are Rosennean in nature – thus archetypically *analogue* – and that they would therefore require an infinite number of models to completely formally represent them, or an infinite number of bits for accurate digital representation. But we have also concluded that our
Natural hierarchy is a primarily *digital facsimile* of an *analogue* view of our surroundings. However, this seemingly analogue view is based on the multi-parametric *digitized* form of modeling we habitually and *apparently* necessarily adopt in the human pursuit of representational accuracy. We say *apparently*, because it is only our reliance on *conventional* techniques of computation that makes it necessary to fragment the complementary characteristics of Natural phenomena in order to represent them in a tractable form. We have indicated in a previous publication (Cottam et al. 1998) that organisms appear to resort to a more performant chaos-based scheme of information processing. Chaotic systems have the ability to explore their phase spaces and generate new information in a manner which is more related to their characteristic Lyapounov exponents (Nicolis and Prigogine 1989) than to their characteristic processing-element size, and this makes it possible to increase information-processing *density* rather than merely quantity (Cottam et al. 1998).

![Digital scales Analog inter-scales](image)

**Figure 5:** The analogue inter-scale regions form a second hierarchy which is partially independent of the first scale hierarchy.

On close examination, our original formulation of a multi-scale Natural hierarchy does indeed turn out to be primarily *digital* in character, because its multi-parametric models are constructed through the fragmentation of phenomenological properties. The complex inter-scale regions, however, should be assessed from an entirely different viewpoint, as their properties are essentially inseparable. This particular *analogue* viewpoint is totally inaccessible from a conventional Scientific platform, as it is 'strange' to traditional modeling and conventional computation: it is characteristic of a *holistic* approach, rather than a *reductive* one. We cannot stress this point too strongly: the *second* hierarchy of complex regions is *analogue* in nature, as opposed to the *digital* character of the *first* one. The first *scale* hierarchy is *reductive* towards localization at the right hand side of Figure 5. The second, *inter-scale* complex region hierarchy, however, is *expansive* towards the left hand side, but as Figure 5 implies this is equivalent to saying that it is *reductive towards nonlocality* (Cottam et al. 1997, 2008a).

The intimate inseparability of these two hierarchies creates a singular birational framework within which *any and all* Natural entities and phenomena can be embedded. We believe that computation within this *birational* framework can be closer to Nature than conventional monorational approaches, most particularly for complex and living systems. We conclude that Scientific or philosophical investigations should *always* be formulated birationally, in a way which is related to the Western interpretation of *yin-yang* (Wong 1997) – as a complementary pair rather than an alternation of opposites.

Transition from the right hand side of Figure 5 towards the left involves passing through sequentially-scaled models whose digital facsimiles contain more and more information, and
whose representations approximate better and better the analogue properties they attempt to reproduce. However, we must address the real time accessibility of these models with an eye on the information-processing timescales they consequently impose. Models towards the right hand side of Figure 5 contain limited amounts of information, and they are therefore conducive to rapid evaluation. If the entity denoted by our hierarchy is an organism, then these simplified models facilitate rapid response to an external threat. Models towards the left hand side of Figure 5 contain more detailed information, which would demand more time-consuming processing. This is comparable to the potential of our own brains, where a rapid reactive system through the amygdala (related to ‘fear-learning’: LeDoux 1992) is available to bypass the more accurate but slower processing of the cerebral cortex.

Ultimately, such a birational Natural dual hierarchy describes the past, current or future emergence or evolution of any differentiated entity from its Universal origin in the Big Bang, and the farther we progress towards the left hand side of Figure 5 the more we approach perfect nonlocality. Conversely, the more we approach the right hand side of Figure 5 the more we approach the simple closed-off non-communicating character of pure localization or formal logic. These two extremes of perfect nonlocality and pure localization provide inaccessible spatial dimensional extremes between which any differentiated entity must and can only exist: they are Platonic in their perfection or purity. This makes our usual conception of existence itself a relative derivative of these two absolute models of nonlocality and localization!

The model scales which appear in our first Natural hierarchy each constitutes the totality of information which is required to completely describe the denoted entity at that scale as viewed from outside. This descriptive or containing information, however, is progressively less and less able to accurately represent in detail the entire denoted entity as we move farther and farther towards the right hand side of Figure 5. Each scaled model, therefore, is necessarily an incomplete description, and any information which has been automatically subsumed or contained during its generation is omitted. This contained information is effectively ‘invisible’ at that scale of modeling, and it can be likened to the hidden variables (Bohm and Hiley 1993) which appear, for example, in David Bohm’s treatment of Quantum Mechanics in a realistic setting, where he states that:

\[\text{In the enfolded (or implicate) order, space and time are no longer the dominant factors determining the relationships of dependence or independence of different elements. Rather, an entirely different sort of basic connection of elements is possible, from which our ordinary notions of space and time, along with those of separately existent material particles, are abstracted as forms derived from the deeper order. These ordinary notions in fact appear in what is called the ‘explicate’ or ‘unfolded’ order, which is a special and distinguished form contained within the general totality of all the implicate orders (Bohm 1980).}\]

We believe that Bohm’s explicate order corresponds to the denoted entity of our first (single) Natural hierarchy: it consequently appears in various forms in a multi-scale representation. His implicate order at a specific scale would then be the entirety of that scale’s pre-emergent information, and his explicate order would be the scale’s post-emergent model description, or containing information. But where is the post-emergent contained information located in our

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12 Godel’s incompleteness theorems (Goldstein 2005) indicate, as might be expected, that the description we are presenting is itself incomplete, as any model involving Rosennean complexity must be.
birational hierarchy? We submit that the total hidden or contained information in a birational natural hierarchy constitutes the totality of the complex inter-scale regions. But, for a specific scale, will the contained information be its pre-emergent complexity, to its left in Figure 5, or its post-emergent complexity, to its right in Figure 5? Well, neither and both!

Figure 6: (a) The sequence of elements on transiting from scale A to scale B; (b) approximate contained information associated with scale A after the emergence of scale B; (c) the dual hierarchy with the quantity of contained information better represented; (d) corrected analogue-to-digital and digital-to-analogue interfaces inserted between scales A and B.
We pointed out earlier that a Natural hierarchy constitutes an interface between analogue and digital representations, and that in order to constitute a complex region we must insert at least one facsimile of our entire hierarchy between adjacent scales of the hierarchy itself. More precisely, if we are to identify the extant scales of a Natural hierarchy as digital representations and the complex regions as analogue ones, we must establish the scale sequence illustrated in Figure 6(a): transition from digital scale A to digital scale B requires first a digital-to-analogue hierarchical interface, then the expected analogue region, and lastly a hierarchical analogue-to-digital interface.

While we might intuitively expect the contained information of scale A to constitute uniquely a pre-emergent complexity to its left, prior creation of scale A will also have generated to its right a potentiality for creating scale B approximately equivalent to the A-to-B analogue region indicated in Figure 6(a). The subsequent emergence of scale B will recursively adapt, or slave (Haken 1984) scale A and its associated information (and indirectly all other extant scales). Following this emergence of scale B, the complete post-emergent contained information associated with scale A will then be approximately as shown: it will neither be the entire complex region to the left of A, nor the entire region to its right, but ‘part of each’ (Figure 6(b)).

As usual, it is much easier to describe the character of a static state than to specify how it comes into being. As Pirsig (1991) suggests:

“A Dynamic advance is meaningless unless it can find some static pattern with which to protect itself from degeneration back to the conditions that existed before the advance was made. Evolution can’t be a continuous forward movement. It must be a process of ratchet-like steps in which there is a Dynamic movement forward up some new incline and then, if the result looks successful, a static latching-on of the gain that has been made; then another Dynamic advance; then another static latch”.

The complex contained region surrounding a specific scaled containing model of a denoted entity constitutes the ecosystem from which that scale will appear to have emerged. This means that at every scale of a Natural hierarchy there is a combination of containing information and contained information – the extant model and its associated complex region, respectively – which makes up a {denoted-entity model – denoted-ecosystem model} pair, and which completely describes the denoted entity at that scale. Transition towards the right hand side of Figure 5 is accompanied by a progressive reduction in the containing information from model to model, corresponding to an increase in the amount of hidden contained information: transition towards the left increases the containing information, and the contained information decreases. To a first approximation the total information at each scale will be the same, resulting in the modification to Figure 5 shown in Figure 6(c). This now makes more sense of the way in which we inserted the analogue-to-digital and digital-to-analogue interfaces in Figures 6(a) and 6(b). The corrected configuration is illustrated in Figure 6(d), where the digital representations and the analogue representations penetrate into each other.

A major disadvantage of monorational approaches to Natural multi-scale systems is that relationships between the different scales must be ‘inserted’ from outside. The birational hierarchy we have described takes account of static properties, but it also intimately integrates both structure and processes of change through an overall context-dependent partiality. Not only are the individual scales partially integrated and partially autonomous, so are the individual sub-hierarchies themselves: change in any property of any part of a birational Natural hierarchy results in partial correlated changes in every other property. We believe that computation within
this birational framework can be far closer to Nature than conventional monorational approaches, most particularly for complex and living systems.

Unavoidable Consequences and Conclusions

The imposition of birational ecosystemic principles on the conventionally monorational domains of Science and Philosophy results in an unexpected and unavoidable consequences. Principal among these is a change in our perception of existence, which in a monorational scheme must be absolute. Not so in an ecosystemic context, where entities or phenomena ‘exist’ in a context-dependent intermediate Aristotelian condition relative to the spatiotemporally-dimensional Platonic extremes of pure localization and perfect nonlocality. These two extremes themselves ‘exist’ as a pair of complementary paradigms related to Newtonian Mechanics and Quantum Mechanics, respectively, which are found to be of parallel importance rather than discarded imperfect precursor and currently-adopted undisputable ‘reality’. Existence itself is fragmented between numerous organizational scales which are recursively coupled by facsimiles of the entire bi-paradigmatic structure itself to create a multiply-fractal ‘living’ hierarchy. Nowhere is there a functionally isolated entity or phenomenon; only degrees of interconnectedness, from the weak to the strong, but never zero or complete.

Our original mission was to bring all of Science under a generalized umbrella of entity and its ecosystem, and then characterize different types of entity by their relationships with their relevant ecosystems. This can be achieved within the birational ecosystemic hierarchical framework we have described, where any and all definable entities and processes are contextually-dependent and consequently more or less coupled or autonomous.

We noted earlier that an ecosystemic approach could be related to Turing’s advances in code-breaking (Erskine and Smith 2011), through the insistence on relating an individual coded message to the globality of its ‘environment’ of place, date, time, weather, … but also that it is impossible to generate in a digital computer any phenomenon which depends on globally-coupled properties, such as intelligence, life or consciousness (Cottam and Ranson 2012). Birational ecosystemic hierarchy holds out the exciting prospect of fabricating more generally applicable computational machines, conceivably bypassing the ‘red brick wall’ of complexity currently facing artificial intelligence and opening the way to the development of real non-biological intelligent systems.

![Figure 7](image-url)

Figure 7: (a) A conventional two-component ordered state; (b) the alternate ordered state.

The relationship between life and entropy provides an excellent example of the way in which the birational approach creates new viewpoints. Entropy is most usually referred to as the inverse of order. Given equal numbers of black and white balls, the most ordered arrangement is taken to be with all the black balls together and all the white balls together, as in Figure 7(a). Reasonably, the least ordered, most entropic arrangement would then be an alternation of black and white balls as shown in Figure 7(b). However, this is really an alternate kind of order, which is found in the atomic arrangement of crystalline gallium arsenide, for example, where
atom types alternate through the crystal (Cottam and Saunders 1973). If we associate entropy with the inverse of order, we now need two different kinds of entropy to associate with the two different kinds of order. Here again we meet with a pair of dimensional extremes enclosing reality. If we start from one of these two extreme ordered states and move towards the other we would expect the initial state’s associated entropy to progressively fall away, and the other state’s associated entropy to progressively rise. We suggest that life colonizes the mid-region between the two kinds of order where the total summed entropy may be lowest.

Complementarity is the order of the day, whether this is unformalizably-intimate, as in recursively-functional organisms, or formalizably-distant, as in the loosely-tractable ‘inorganic’ subjects of conventional Science13. Complementarity may be approximated in various ways, from its most simplistic representation as a pair of opposites to the extreme complexity which apparently characterizes life. Science habitually resorts to a two-part representation: first the institution of a set of non-recursive orthogonal parameters, whether dependent or independent, then the establishment of a formal, preferably linear relationship between them14. This effectively ejects recursively-functional living organisms from Science’s purview; thus Rashevsky (1954) and Rosens’ (1991) particular focus on the interrelational characteristics of life.

The birational ecosystemic association is fundamentally one of combined segregation and integration, neither one nor the other, where predominance depends unavoidably on context. Differentiating segregation leads to the reductionism of conventional Science; unifying integration leads to the holism of human relations. Either of these can be embedded in the general hierarchical scheme we have presented. We believe that computation within this birational framework can be far closer to Nature than conventional monorational approaches, most particularly for complex and living systems.

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13 Note Robert Rosen’s (1991) description of biology as “the study of the dead”.
14 An excellent example of this approach can be found in electronics, where a resistive component is first characterized in terms of the institution of non-interactive orthogonality between two functionally-dependent parameters – voltage V and current I – and then the component’s resistance R is established by the formal relation R = V/I.


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