Information as Communication: The New Eco-Informatics

John J. Kineman[1] and K. Anil Kumar[2]

[1]Cooperative Institute for Research in the Environmental Sciences, University of Colorado, Boulder, Colorado 80309 USA, John.Kineman@colorado.edu

[2]Department of Chemistry, Sri Satya Sai Institute of Higher Learning, Prashanti Nilayam, A. P., 515134, India. anilk3@gmail.com

Abstract

The goal of eco-informatics is to represent natural biodiversity and ecosystem phenomena, and to communicate such information to society, for science, valuation, management, and policy. Communication is the key, for without it information does not inform. We argue that past approaches to building databases and information systems were incomplete, and thus less communicative than needed regarding ecological phenomena. Information systems until recently have been limited to data about the physical state of the environment and biological components. While this worked well for physical systems, which can be modeled mechanistically, based on observable states and the application of general mechanistic laws, living systems have entailments beyond such mechanisms. They tend to generate additional system-dependent laws, or 'functions' that are internal to the natural system, and correspondingly must be represented as internal to the informatics system. Robert Rosen's theory of 'relational complexity' is an appropriate foundation for new thinking about the entailment structure of living systems, and how to reflect that in informatics so it may represent living systems better. We derive from Rosen's work, specifically his 'modeling relation,' a working theory of natural communication that can be implemented in informatics. This approach represents nature in terms of a complementarity between states and 'functions.' Functions act as system attractors or potentials, inducing but not determining change. The relationship is inherently complex, and when implemented in informatics it can support exploration of complex behaviors through simulations and scenario-building. Ecological functions, the 'missing element' in informatics, can be represented (but not totally specified) in the informatics architecture as a generalized form of ecological 'niche' model. A generalized form of niche model can be integrated with the database design. Relational complexity itself describes a natural form of communication. Designing informatics in an analogous manner suggests that it too will have better communication capacities. This, we argue, will allow informatics to accomplish its goal to communicate and inform. Various traditions, most notably from the East, present a view of the world as fundamentally complex and in constant communication with itself. To have a scientific way of representing this concept will improve integration across society and with various approaches to valuation, including indigenous values and perspectives. These needs are met in the proposed relational design for eco-informatics and enterprise development. A demonstration of how niche modeling can be used to represent an ecological function (the primary productivity of India) is appended. We believe the theory and implementation described here is a promising foundation on which advanced informatics capabilities may immediately be built to address the complexities of ecosystem management and to help meet pressing societal needs.

Keywords: Information, Communication, Relational Complexity, Niche Modeling, Ecosystem Informatics.

Introduction

The goal of ecosystem informatics is to support science and inform society so that important choices can be made (Cushing and Wilson, 2004). This requires that informatics provide effective communication of not only what exists in nature, but also what it is prone to do, so that we can understand and manage it. To address this need we re-examine information theory and propose a natural philosophy of information and communication that can be applied in an appropriate design for eco-informatics.

Our inquiry began by asking if there may be a better foundation for thinking about ecological systems than the physical concept of states and universal laws governing their change. It has long been a slogan in ecology that *"the whole is greater than the sum of the parts;"* but to date there has not been a precise understanding of this principle. As we consider the needs for ecological and ecosystem informatics, however, this question becomes paramount – for if we are indeed leaving something important and natural out of those information systems, which will be used to support advanced research and decision making, we can be sure some potentially important limitations will result.

We believe that a new foundation is needed to reflect natural complexity in ecosystem science and informatics, and especially to serve ecosystem management. In particular, we need not only data about system states, but a formal representation of ecological functions as potentials or attractors of a natural system. Such potentials have a real effect on how the system changes. That effect can be understood as involving the transfer and use of information to induce change.

The idea that nature is entailed through information transfers grew out of scientific theory about relational complexity developed by Robert Rosen (Rosen, 1985). It was also found to correspond with ancient Vedic teachings of India that describe nature as a system of communications (Kumar, 2006). The idea of information in nature has been around for some time, but here we provide a theory to allow practical use of the concept. Applying this idea required little more than taking seriously what most ecologists have sensed – that nature is fundamentally complex in ways that distinguish it from a mechanism. Modifying Rosen's theory, we derived a relatively straightforward way to represent this kind of complexity and wholeness. We employ ecological niche models to represent the less tangible "attractors" or "potentials" of the ecosystem. We suggest that eco-informatics systems or enterprises can easily be built on these principles, making them more useful for studying and simulating natural behaviors that are impossible to quantify or predict otherwise.

A great benefit of re-evaluating the foundation of ecosystem informatics in this way lies in the possibility that such a system will itself be more capable of meaningful communication within the human system of science, valuation, management, and policy, because it is entailed the same way as natural communication. Everything that is system-dependent should be incorporated into the informatics enterprise to accomplish this. Scientific communication for policy and decision making has often been ineffective because it does not communicate complete information, i.e., about states and their relationship with system-dependent functions. Ecosystem management requires informatics that are capable of delivering both and exploring that relationship. .

From Mechanism to Relational Function

Although many useful elements of theory have been adapted from the physical sciences, ecologists have generally found it impossible to follow the construction of physics as a foundation for ecology. Ecology has thus greatly suffered from lack of a central theory of its own (Simberloff, 1981). Virtually every new assessment or synthesis of landscape ecology calls for "new thinking" (Scott, et. al., 2002). Here we adopt some ideas from Robert Rosen to establish a fundamental theory on which we can expand ecological informatics to include functional elements of the ecosystem.

Speaking of "function" of a living system is unavoidable in ecology. Functions may also be understood as ecological potentials. For example, the function of providing tiger habitat creates a potential that tigers could realize in some important way. The ecosystem, in this sense, 'anticipates' tigers.

Landscape ecology often refers to "pattern and process" (Turner, Gardner and O'Neill, 2001). Process tends to be dealt with mechanistically, imagining it to be limited to dynamics that build patterns from the 'bottom up' according to general laws (with external origin). There is also a 'top down' causality that comes as a whole system interaction, or feedback from the greater nature of the whole to its parts. This produces system-dependent laws of internal origin and uniqueness. We refer to these as system functions, which may arise as a feedback or interaction between components of a system and their context. These contextual relations play a role in defining what is produced inside the system. Functions thus emerge from within the system and are part of the whole organization. Such functions affect both the behavior and existence of various components, and also induce change in other related systems.

Patterns can be seen to result from the influence of both processes and functions. For example, do the organs in the human body define the organism as the sum of their processes, or does the organism define and produce the organs as a realization of its functional requirements? Both are true.

In mechanistic theory, physical states and their laws are re-constructible into predictions of what the system will do. But in living systems, system-dependent functions, which may be imagined as local laws, intervene, making behaviors unpredictable. Consequently, those things that can be generally "predicted" represent a peripheral aspect of ecological and social systems – their physical constraints. What we wish and need to know about them is precisely the things that are hardest to know and predict because these systems are, due to functional entailments, adaptive, self-defining – elusive.

Adding functions as relational components in our theory of ecosystems is a way of representing influential aspects of the whole as if they were fuzzy parts, and thus being able to visualize, comprehend, and work with them. If we accept this on the practical level, it follows that such fuzzy parts should be treated in ecoinformatics as components of the natural system. They must therefore be represented in the information system in relationship with the well-defined components or states. Because of the legacy of reducing knowledge to physical concepts we are used to the idea of observing and measuring states of a natural system and representing these as empirical 'data.' We have not had the habit or the design criteria to represent local functions as effective entailments.

A Brief History of Information

Our concept of data and information for environmental science dates back to the 1950's. It is almost entirely about physical systems (Kineman, 2003). Information was defined by World War II cryptography research (Corning, 2001) in terms of one-way transmission models, and this formed the basis for our primary theory of communication surviving until today. Information itself was associated with processes of life and described in terms of thermodynamic concepts of order in Erwin Schroedinger's famous book "What is Life?" In particular "neg-entropy," the opposite of entropy, was defined as a measure of order. Shannon took this as a measure of information, deceptively replacing Boltzman's thermodynamic variable 'W' with the probability of any given event. This yielded the formula:

$I = -\log_2 P_a$, where I is the 'amount' of information,
and P_a is the probability of event 'a'

Their concept of information was *"that which reduces uncertainty,"* which led to the definition of information as "*That which makes a change in probability assignment."* (Tribus, 1971, cited in Ulanowitcz, 1997). These communication theories were very linear in concept, as in the communication model adopted by Claude Shannon, Norbert Wiener, and Warren Weaver (Fig. 1).

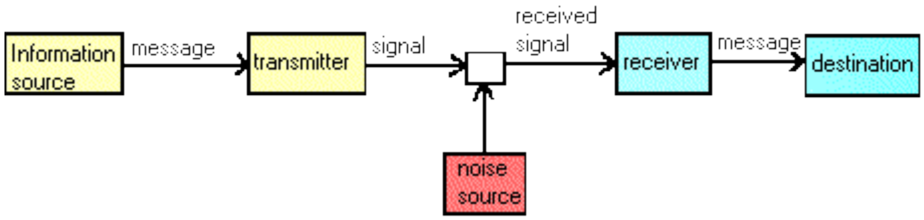


Figure 1

Shannon-Weaver Model (Underwood, 2003)

The linear concept of 'information-as-transmission' (Figure 1) permeates our data and informatics thinking even today. Information is considered almost a "thing" that goes from one location to another, or is stored, all the while remaining well-defined in itself. Decoding into bits on magnetic and optical media is a way to record data, which we imagine is the essential component of information.

Critics have pointed out that information isn't removed from its source when it is "sent," and hence it is not actually transmitted or conducted, but replicated. Furthermore, the changes it induces in other locations and systems are generally dependent on the copying procedure (a function) and context (a constraint). Whereas error is depicted as the addition of "noise" in a transmission model, copying error in living systems actually results from incompleteness in the copying procedure and multiple possible recombinations. The improvement in replication of data, by encoding it digitally, applies only to the syntactic aspect of information (measurable states) and thus can theoretically be exact. But when nature itself makes copies, it replicates complex wholes that involve both structure (state) and function (potential). By focusing only on measurable aspects, i.e., states, we thus have a very limited and mechanical concept of information that does not relate very well to natural living systems.

Information Becomes Informatics, But At What Cost?

As Data Centers were created in the 1950's to support emerging environmental observing programs, they had little question about the complex aspects of information. Data became even more objectified in "data sets" and data products, which could be distributed as goods.

These concepts of data and information worked very well for describing physical systems which in general can be described in mechanical terms. Nearly all World Data Centres that became established until recently were devoted to physical measures. Despite numerous biological programs since the 1950's almost no biological or ecological data centers were created for global studies (with the exception of research labs and museums, which developed their own localized resources). With the advent of "global change" programs following inauguration of the International Geosphere-Biosphere Program

(IGBP) in 1986, more general interests began to emerge regarding living and social systems, but still only a few Centers were established for biological data. A likely reason for this is that physical measures are well-defined and generally applicable to many contexts, whereas biological and ecological measures tend to be system-dependent and contextual, requiring a vastly different approach to their organization. Furthermore, having a small set of consistent measures that apply generally, made it profitable for companies to invest in instrumentation. The development of instrumentation since the 1930's was specifically cited as one reason for conducting the International Geophysical Year in 1957. During that year the only biological observations were in Antarctica, as a result of having to travel overland to get the physical data.

The ability of such data to "communicate" information, however, was based on the general nature of physical laws. Everyone acquiring these syntactic representations could add back the semantics and use the data accurately in physical models. But this ran afoul quickly with regard to representing living systems, quite simply because system-dependent functions exist semi-independently of measurable states, and we have had no good way of recording it.

The first attempt to correct this problem was to provide "metadata" or "data about the data." In a way metadata is a first attempt to restore knowledge of function to the syntactic components measured, but a very limited attempt that only documents some of the research context, not the natural system context itself. The advent and wide application of "Geographic Information Systems" (GIS) introduced a technology that centered on representing patterns in or derived from data, patterns that can also act as functions modifying state variables. This was a further step toward capturing system functions, but its techniques again focused on physical and statistical representations associated primarily with observations and introducing some exploratory work with representing system potentials. Recent interest in niche modeling is a promising aspect of this development. Nevertheless, this is the current status of environmental "informatics," which has yet to become truly ecological, i.e., expressive of the natural relationships involved in living systems.

What is interesting about biology and ecology is diversity and innovation, and yet these very things are what make it difficult to define and collect data. The appropriate instrumentation for recording diversity and system-dependent phenomena, is a diverse, distributed system, which we have today in the Internet. It is neither surprising nor coincidental that the US National Biological Information Infrastructure (NBII), the first general biological data facility, is also the first truly distributed data facility, made possible by internet infrastructures. This, combined with GIS architecture, provides the kind of "instrumentation" that is necessary for observing complex systems, but we have yet to realize its full potential to represent ecosystem functions.

We point out these shortcomings of current information thinking because it directly parallels the problem in ecology and ecosystems thinking, and the continuing problem in ecosystem informatics. That problem is that living systems are complex and not well characterized by linear, predictable sequences of events and causes that can be represented by state measurements alone, i.e., physical concepts. It is that the important elements of ecosystems and their management are functional relations, not measurable objects. Correspondingly, an informatics system that treats information as a physical unit will miss the mark in ecosystems science and management.

The main criticisms of traditional theory that underlies most information and communication concepts are:
The mechanical "conduit" and "transmission" metaphor,
The lack of contextual influence of system functions,
The lack of reference to meaning (only state "syntax" is represented).

What is Information?

To capture some sense of the whole of living systems, we need a broader, relational information theory. The idea of thermodynamic order, which is a general system measure, has been applied for this purpose, most notably in regard to "network thermodynamics." Robert Ulanowicz (Ulanowicz, 1997) for example, defines information in thermodynamic terms as: *"Effects of that which imparts order or pattern to a system."* He was saying that information is some kind of action imparting order and changing probabilities, but he did not say what that action is. Peter Corning (Corning, 2001) attempted to fill the gap in communication theory with a concept of "control information" which presumably would be the *effects of that which controls a system,* particularly in the mode of catalytic processes. This too, begs the definition of what produces control information. Most definitions of information, even modern ones, say what it does rather than what it is. These are indeed things that information can do in an ecosystem, but perhaps not everything. We need to be more general than that for design purposes.

The term "information" means literally *that which causes or changes form within.* Form, in this usage, means structure in a syntactic sense. Hence information is distinct from structure, i.e., states, and is what causes changes in state. A complete shift can be made from information as some additional syntax (a physical concept), to information as essentially semantic. For example one definition in cybernetics is *"the meaning of the representation of a fact (or of a message) for the receiver."* (Principia Cybernetica Web, 2005). But then we have to say what "meaning" is and how to represent it. One can ask: *is there something other than the state of a system that is involved in a change in state or meaning?* The field of biosemiotics (Hoffmeyer, 1997) attempts, with limited success, to add the contextual and semantic elements this question implies, but retains much of traditional information theory, including its linear transmission model (Corning, 2001).

In ecosystem management and policy we are as concerned with functions and meanings as we are with states, and most scientists recognize that these are different. For example, the fact that a given system has a high level of measurable primary production may miss the possibility that the system is overproducing and has a potential to catastrophically flip to another condition (i.e., 'crash'). Where does that potential exist? Its scientific and political importance, the difference that is induced by its meaning, is in human society.

The meaning itself arises from an interaction between two systems (the ecosystem and a human context). As a system function (potential for ecological change) it exists in the ecosystem that has feedbacks regulating stability. It is better described as an "attractor" (as in chaos theory) than a mechanism, because its effect is real but the precise result is uncertain. If we think of it as an information component, it is a semantic complement of a state or set of states. Since it has real effects, we consider it to be an actual component of a natural system that can drive ecosystem dynamics in various directions. Note that it does not matter for descriptive purposes if we believe this semantic component is ultimately explainable in terms of a much larger mechanism, as long as we don't limit it to any given mechanism. That proposition properly sets the explanation beyond reach (an infinite regress), but the complementarity described by state-function relations is very present and open to exploration: A function can summarize even an infinite number of mechanistic interactions.

Thus we refer to semantic influences as *'system functions'* in the sense of one system having an influence on, or role in another, that role being its function. For example, "pumping blood" is the function of the heart with respect to the semantics of the human body, and the meaning of pumping blood in this context is continued life. Meaning is a final function, or semantic consequence. A system context is required for there to be a function, which itself is a relational system property rather than a "part." Combining the concepts of function, which induces change, and information, which induces change, we conclude that they are closely related. We are thus constructing a view where relationships are describable as information exchanges between state and function.

We can now offer our view that, ***real communication is a dialogue between systems that imparts a functional difference to them. This in turn induces measurable but partially uncertain changes in system states.*** This agrees closely with another recent definition from cybernetics, that information is associated with *"the degree to which one variable of a system depends on or is constrained by another"* (Principia Cybernetica Web, 2003). We can be even more explicit and say that ***"information is the means by which one variable of a system depends on or is constrained by another."*** This is the most useful definition because it easily translates into a special kind of model, the niche model. Note that a "variable" is not restricted in this definition to measurable states, but may also be something that is inferred from such a model. We will use this concept as our theory of communication, and hence to propose a new system design and architecture for ecosystem informatics.

A Theory of Natural Communication

"I think the definition of information has to include some sort of semantic relation. Information is inherently relational-- it is only information if there are referents attached and it is the referent that makes it "information". This is why raw data, divorced from all referents, is not information." Judith Rosen (Rosen, 2005)

Robert Rosen (Rosen, 1985) developed a theory of natural complexity involving the idea that natural systems are describable in terms of "modeling relations." Modeling relations are the interplay between natural systems and representations of them (Figure 1). This kind of relationship is well-known in epistemology as a picture of what we attempt to do in scientific modeling. We attempt to copy natural behavior into a model (encoding) and we use that model for prediction or management (decoding). The modeling relation can also be taken as a very general picture of informatics, where the "formal system" is informatics and the "natural system" is nature. Since a goal of ecosystem informatics is to affect nature in some way through management, it's decoding actually results in natural changes. So decoding is not just part of the epistemology, it can also refer to changes induced by application of the model. We can thus say that the formal system represents a *functional specification* for nature that may be both descriptive and prescriptive, but necessarily with error. The necessity of error arises from the incompleteness of information transfers in both encoding and decoding. Any system that attempts to copy another can only do so with regard to a subset of its full nature. Each system in this kind of relationship is actually an abstraction of (literally "taken out of") the other.

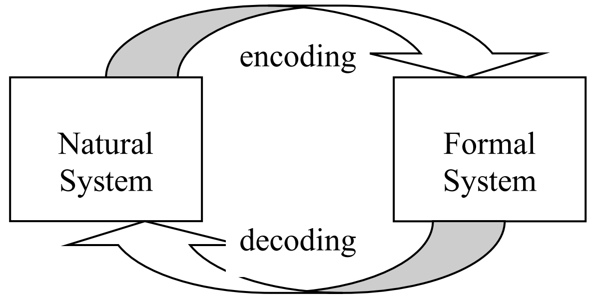


Figure 1

A very similar idea of mutual encodings was captured in the famous drawing of Escher, of two hands drawing each other (Fig. 2). The implicit complexity is what intrigues us about this image. We can imagine that slight errors in drawing might lead to a continuously changing picture. Furthermore, if there are influences from the environment/context, say the lighting in the room, this too will induce some change in the result by affecting the encodings. These kinds of influence cannot be specified mechanically. Who can write an equation for how a change in lighting will alter the drawing under these conditions? However, carrying the analogy back to informatics, we can provide information about the lighting and about the mutual encodings and the systems between which encodings and decodings take place; and this information can be available for further analysis, to determine common patterns or perhaps analogies with similar circumstances. Having these key information elements, we may also be able to determine the dynamic boundaries that such a system with these components may have; scenarios that can be explored. Ultimately, we are providing scientific information to help others create art – which is management, policy, ethics and social life. We are not telling them how to live or what to draw, and yet even ethical

Figure 2

choices and value beliefs can be represented in this framework, as natural or human functions.

There are ways in which the modeling relationship itself describes a natural process. It obviously describes a human capability. If you imagine going to Paris, you have in your mind a model of Paris, the trip, yourself, the weather, etc. It is also apparent that many organisms operate in a similar manner, making models of nature and responding to them. Even plants do this to anticipate seasonal changes, although we presume the process need not be cognitive or self-aware. It is possible, in fact, to think of living nature entirely in terms of such modeling relations. This follows from Rosen's theory and is an explicit representation of what Gregory Bateson called "information in nature," where information is "encoded" and "decoded" to represent and induce the alteration of states.

The objection may arise that not all systems have such models. What about primitive life and physical systems? Where no model-driven behavior is apparent, the diagram can still be applied as a more general theory. It is merely the case that encoding and decoding commute, and each system copies the other exactly, removing the difference between model and system. We could say, in this case, that the system is its own model, and thus it follows only the general laws (functions) that we use to define the material system. This would be the case for physical systems that are defined as mechanisms, which itself is a subset of the reality of a natural system, abstracting only precise states (measurables) and not the internal functions. Proposing an internal model is thus unnecessary for a specific theory of mechanisms, but it is important for complex systems and as a general theory for both. We can also say that in the case of physical systems, the formal component is not differentiated (or is simply not independently organized) to provide influences from an independent model. We thus have a framework based on information exchanges that applies generally to all known phenomena from quantum to cosmos.[1]

The essence of this approach is to view living system complexity as resulting from such modeling relations, which then allows us to recapitulate that presumed natural entailment in the informatics system or enterprise. This idea has appeared in ecology before, although not with a fundamental theory that generalizes it. C.S. Holling's idea of "adaptive management" is nearly an identical concept in its intent, where the results of management would be assessed iteratively, by going around this kind of encoding/decoding loop many times adjusting to the effects of past management.

The Step from Theory to Practice

To translate the modeling relationship, which is really a natural philosophy, into a natural science that can be implemented in an informatics system or enterprise and tested, we had to modify it for practical use. When the epistemological relationship in Figure 1 is considered natural, and we attempt to understand it as such, what we are capable of confirming in nature is a slightly different dichotomy than imaged philosophically, because we cannot observe whole systems. What we can observe or infer is more like what is shown in Figure 3. It is the same diagram and same basic relationship, but this time it is labeled according to what we can either observe (on the left) or infer (on the right) about a natural system. Because of these two abilities, all systems appear to have both components in relationship (whereas what we assume is really happening is shown in Figure 1). We can imagine Figure 2 nested inside Figure 1, in the box on the left labeled "natural system," as this is what science and the informatics enterprise will see.

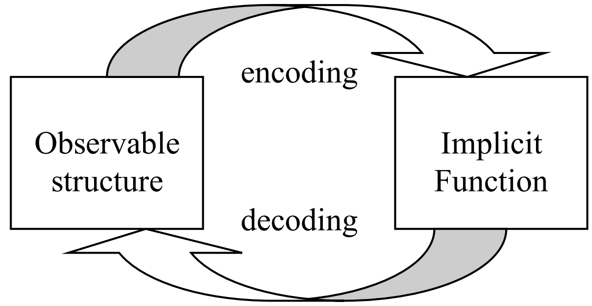


Figure 3

Because this relationship is essentially two systems copying each other, it has the ability to be complex. The copying operations create a mutual information transfer that induces unpredictable change in both systems. Uncertainty arises in the process of abstracting information in each direction, because it is uncertain what information will be abstracted from the whole. The greater environment or context influences (or constrains) the relationship by affecting the abstraction. The encoding and decoding inductions reside in the outer environment of the relationship and are thus not entailed by either system in the modeling relation. In this sense the "modeler" (meant metaphorically) is part of the context. It is one of the unique features of Rosennean theory that entailments are considered from both above and below. In other words, it considers dynamics, which are non-complex in Rosennean terms, but also the influence from context, the later being most important for living systems and the source of complexity.

Figure 1 represents a natural philosophy of complex relationships that implicitly involves similar relationships, built above and within this picture on each side and without limit (an infinite nesting of Figure 1 inside itself). The infinite expansion is philosophically necessary to complete the system semantics from all the possible relations in nature. This captures the ecological concept that "everything is connected to everything else." It is implicit that it presents a view of the relationships in terms of the more proximal ones of interest and more distal ones that appear in the nesting.

However, in the translation to a relational theory, which Figure 3 shows, these implied contextual (larger and smaller) natural relations, become represented differently than an infinite nesting. They are instead distributed at the same level as the primary relationship of interest, in many structure-function relationships that can be represented as a network of relations. In this way, whatever is needed in the analysis can be added as another structure-function link. The result is a representation of a fully complex adaptive system that represents nature as closely as knowledge will allow, and makes the functional relationships available for scientific testing. A system designed this way is a simulator of creative and adaptive possibilities that depend on the constraints of its environment.

Indeed a very similar idea to this has been used as a basis for simulating life in cellular automata and artificial intelligence.[2] We think it is an adequate representation of complex living systems for the purpose of designing how we collect and organize information ourselves, i.e., the informatics enterprise, recognizing, as the Natural Philosophy would dictate, that all information is incomplete. It is thus important to note that the structure of the informatics system along these lines is not itself a model of the ecosystem for two reasons. First, it is at best a simulation, since we have translated what is presumed natural (Figure 1) into what can be simulated (Figure 3). Second, aside from practical or experimental error, there is a threshold of knowledge in this theory of nature – an indeterminacy. This means that even an exact duplicate ecosystem built on the same natural components would not necessarily replicate behavior. At best we can explore the range and likelihood of behaviors and assess possibilities. It is partly for this reason that explicit representation of each hypothesized function, or system potential, is valuable. The goal is understanding the system behavior better than we could by working with states alone. Human skills will be required (by the users of the informatics) to reach decisions and weigh values based on possibilities and probabilities. The implication of this architecture is that it will help us 'think' and communicate like nature.

What Is communication?

We are now ready to put these relational concepts together to form a theory of communication suitable for informatics design. Communication involves information transfer, and we have identified information with "functions" inferred from a system and complementary to its structure. Modeling relations of the kind discussed are infinitely constructable, by matching up structures and functions. The modeling relation itself represents communication within a given system. When at least two instances of the modeling relation are paired, as in Fig. 4, communication extends externally, to another system and context.

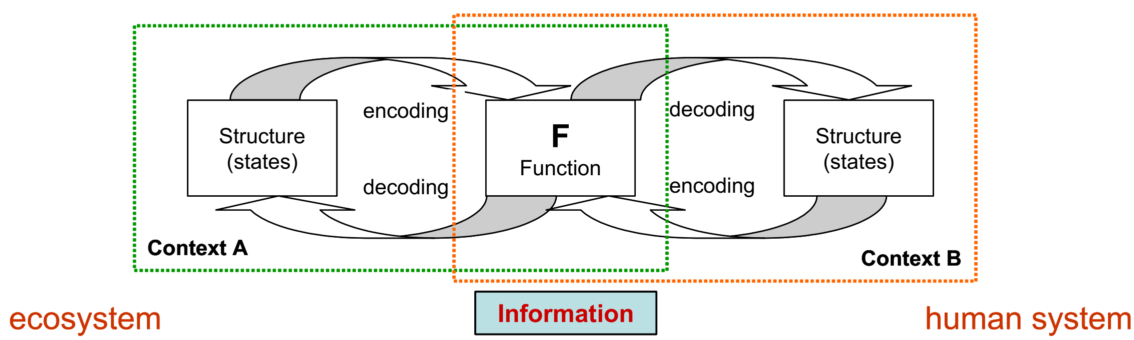


Figure 4

We can see that functions become the information that translates between observable conditions and changes them. In the example shown in Figure 4, we can imagine a landscape pattern that is part of an ecosystem in Context A, a functional inference from that pattern, which is a potential of some kind, and then an interaction of that potential with another system, say certain measurables in human society in Context B. In this way ecosystem and society are in communication, through functional information transfers. This is very similar to Peter Corning's idea of "control information" (Corning, 2001). It is information altering system states from the "outside," i.e, from a context.

Now if we ask what is important in ecosystem informatics, knowing the structural patterns or knowing the functional potentials, it should be clear if we believe this communication model that one would want to know the functions at least as well as the patterns. Furthermore, it is the functions that will communicate best with policy, ethics, and other elements of society.

Another point to stress regarding Figure 4 is that function in context is what creates meaning. For example, an automobile in your garage means nothing without knowing its function. Knowing its function it means you can travel. Its meaning changes if it is in someone else's garage. In the diagram the two example contexts establish two different meanings for F, the function that is in communication between the two systems. If F is, for example, potential primary production based on climate, F means certain energy and trophic possibilities in Context A. In Context B it may mean alleviating hunger. The functions are thus necessary in order to interpret meanings, and thus to communicate meanings. That multiple functions and meanings are possible can also be demonstrated. If very high production is the function resulting from energy subsidies and crop improvement in Context B, meaning prosperity for all in the human system, that meaning in Context A may be different, it may mean overproduction and future crash. Each of these possibilities can be represented in this kind of architecture and each can be documented for use in informatics.

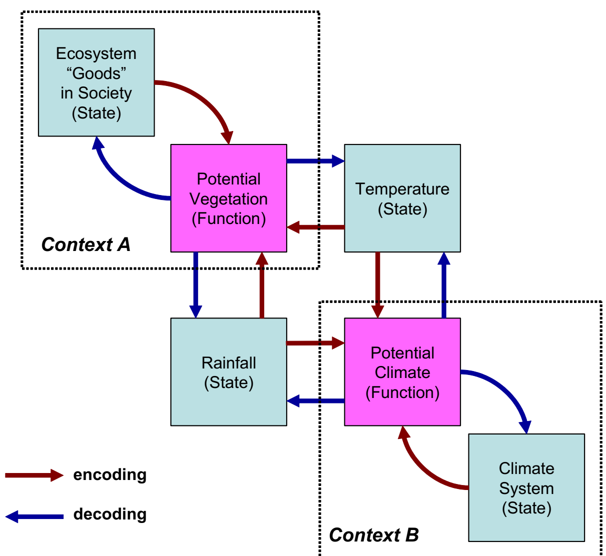


Figure 5

As a more explicit example (Figure 5) we diagram a simple analysis of communication between an ecosystem service (goods from vegetation) and climate, now involving six modeling relations and explicitly representing data sets for temperature and rainfall, and models for potential vegetation and climate. More variables, of course, can be involved as needed.

Each of the colored boxes in this diagram can have explicit representations in an informatics system. Specific state variables are already standard components of a GIS database. The functions can be represented by adding a new architecture to the GIS system, built along the same ideas as "entity-attribute" relations, which are its current foundation. The new architecture would instead have "model-attribute" relations, using software that in large part already exists. Doing this is feasible today, although it requires that we adopt some standard parametric ways of modeling ecological functions. Once this architecture is established, the system can facilitate and keep track of relationships between functions and states, as in Figure 5, or combinations of sub-functions that comprise a "functional cluster" (Figure 6), which, for example, might be an ecosystem service. An unvalidated demonstration of constructing and combining two functional models (from a technique under development) to estimate the ecosystem service of 'potential vegetation' is shown in Appendix I. Feedbacks to a system can be represented by allowing the functional distribution to operate on state variables according to a model of how they would be affected by other functions or processes, such as a spatial dispersion component. The result is a cellular automata that is capable of simulating vegetation encroachment and 'niche construction' (Odling-Smee, Laland and Feldman, 2003), such as soil building.

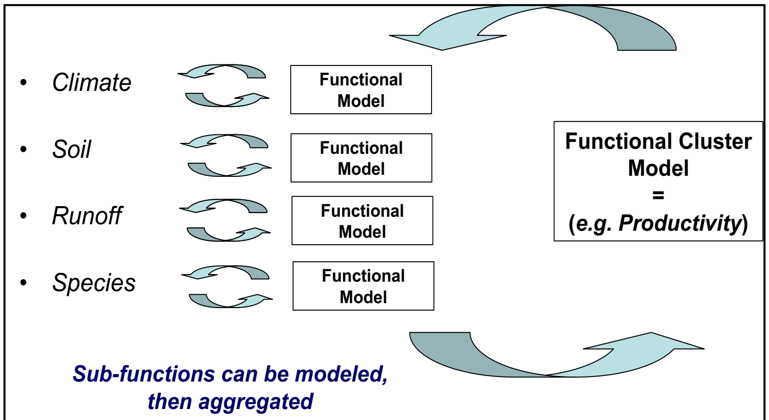


Figure 6: Functional Clustering

Conclusion

Ecosystem informatics is ultimately a very practical field. It does not aim to unravel the mysteries of nature, just to document what can be known. However, how it documents nature affects what we can later do with the information. For this reason it is important to examine the limitations we have placed on natural science information, namely the tendency to represent nature in strictly physical terms. Living systems are not reducible in the same way as physical systems (Rosen, 1991). Ecosystems defy traditional methods of description and are complex in a fundamental way. This has profound implications for the design of ecosystem informatics.

The most basic requirement of a natural science information system is that it should represent nature, follow nature, and serve as a surrogate for nature in human thinking. It is axiomatic that to do this at the level of ecosystems, which are inclusive wholes, the informatics system must be capable of reproducing conditions and behaviors that are close to what we observe. If natural living systems are complex, then the informatics system must represent the elements that, in theory, make it complex. To deal properly with whole systems and their intrinsic complexity, we will need to represent, in addition to state variables, the relationships between states, contexts, meanings, and feedbacks. This can be accomplished by representing ecological functions as active potentials. In this way ecosystems can be represented for informatics purposes, in terms of *states* and *functions*. Functions may be inferred from states, but they are not reducible to states. They are more associated with information, acting as the means for altering states within and between systems.

The key to implementing this idea is to standardize the representation of ecosystem functions in terms of models, which are in the general class of niche models, and include them as compliments to data. This creates a foundation of complex *structure-function* complementarities that is most representative of nature. Simple tools can then allow their relationships to be queried and explored in more detail by users of the system.

The approach constitutes a natural theory of c*ommunication*. This is applied first within the concept and representation of nature, as communication between ecosystem states and potentials. That provides the appropriate kind of information and architecture to communicate externally, between science, ethics, and society. In this social environment communication must be meaningful, which requires communication of function. By representing ecological functions as models and making them accessible along with state variables, we can provide a powerful tool for evaluating options and directing our future. The informatics enterprise can provide a means to evaluate scientific, political, and ethical positions and the results of implementing various plans and policies. By building knowledge of possible outcomes both from an ecological and management point of view, it can guide future choice and define the reasonable boundaries for ethical and political decisions.

We have the tools to do this now for spatial (landscape) informatics. In fact, much of what is proposed here is already in practice in landscape and ecosystem ecology, but it is not unified within a central informatics theory and current informatics systems provide only limited support. Nevertheless, it is entirely possible to build a better system using currently available tools.

Ultimately informatics must be practical. It is ironic to have to describe a radically different view of nature at a deep philosophical level in order to arrive at a simple and practical approach in ecological informatics. However, this is the grand goal of science; to find a more parsimonious way of describing something that is very complex. We believe we have found it, and yet the discovery hardly seems novel, as these kinds of data sets already exist. What does not seem to exist is an understanding of how they should be related, and particularly the tremendous opportunity for bio/eco informatics to build on that relationship.

We also believe that the needs for communication within science and between science, society, and policy would be greatly increased by adopting the approach described here. This is because it is a natural communication structure that is itself rich in entailments, including context and feedback. What works within the architecture to simulate natural behavior operates at the larger level of the informatics enterprise to make communication with society more natural. When decision makers are provided both kinds of information, syntactic and semantic, they have the foundation of what science can provide. We believe that relational complexity theory can provide the necessary design concepts for building such a new and more relevant informatics enterprise.

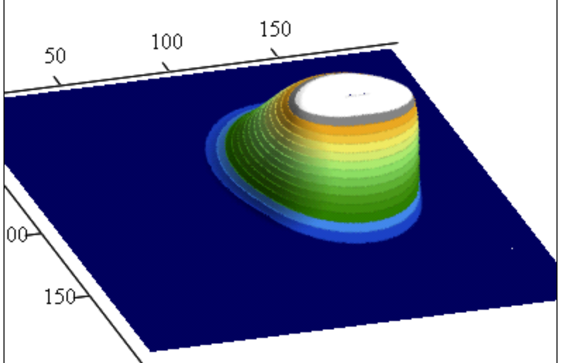
Appendix I: Architecture for Mapping Ecological Functions (AMEF)

Kineman, J.J.

[1]Cooperative Institute for Research in the Environmental Sciences, University of Colorado, Boulder, Colorado 80309 USA, John.Kineman@colorado.edu

A simple demonstration (unvalidated) of using a niche model to produce a functional distribution is shown in Figures 7, 8, and 9. Figure 7 shows how an "n-dimensional niche" might appear in environmental (state) space. The concept is to build this niche

Figure 7: Niche hypervolume



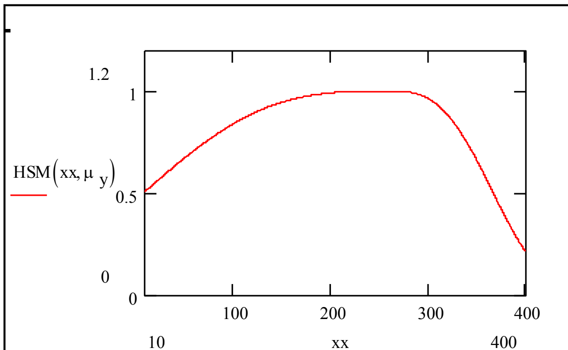


Figure 8: Functional Response to Rainfall

model from environmental variables representing the n-dimensions, and to combine their functional response curves (Figure 8) in an appropriate way to produce the niche hypervolume. One problem of this kind of modeling is that there is no unambiguous way to recompose a true niche from orthogonal components without knowing all the co-dependencies, which is a virtual impossibility. Statistical approximations are available using certain assumptions that make the result generally valid, but at the cost of missing much of the ecology. Some new methods are being developed to build more "ecological" meaning into the construction of such hypervolumes. Figure 9 presents the results of this crude demonstration based on only two environmental variables, rainfall and temperature averaged during the growing season. Because this climate-related potential vegetation would miss suitable conditions for vegetation along rivers in otherwise arid regions, a second model was created to capture potential vegetation from runoff. These two can be combined. The final result is not intended here as a scientific product and no attempt was made to validate it except comparison with a satellite image of Vegetation Index for the same period. The decent correlation given the few variables considered demonstrates the value of this concept. One can begin with available knowledge and data and test additional constraints as needed and hypothesized, iterating the result. The point is to not store this result as a digital map, because it is not data about states of the system. Instead we store this in model form, as a "functor" operating on the underlying state variables, which, in this case, are stored in the GIS as digital maps.

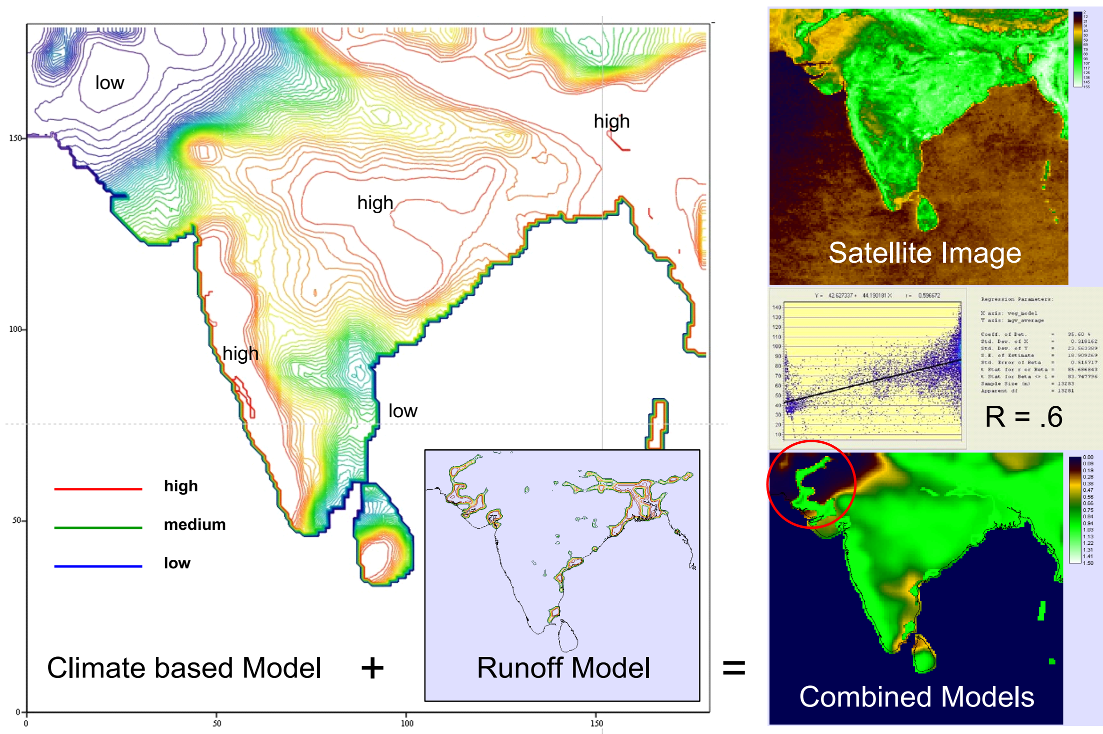


Figure 9: Potential Vegetation Map (Model)/for India

An architecture for building and combining such models is under development using existing Spatial database techniques. This can be implemented as an analogy to the standard "entity-attribute" relationship that is the foundation of GIS technology. However, we expand this concept to a "model-attribute" relationship. The table of attributes can then contain the parameters of the model, the variables used, and metadata about the function specified. In this way we achieve the recommendation of this paper, to represent state variables and functions in a dynamic relationship.

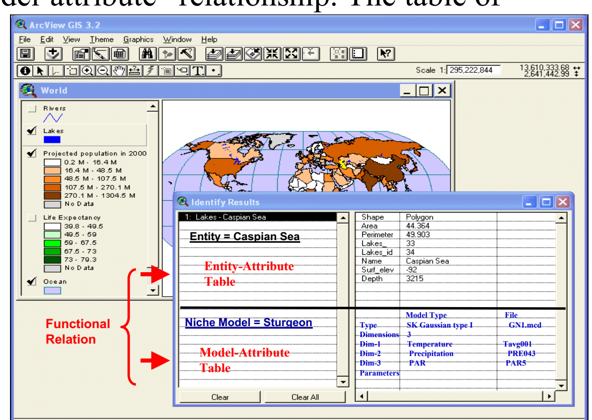


Figure 10: Entity-Attribute and Model–Attribute Tables

Figure 10 shows a typical inquiry in Arc/GIS of an entity-attribute table. The analogous "model-attribute" relationship is written in to demonstrate how it might be implemented analogously. Figure 11 shows the operational linkages of the model, reading state variables from a database and producing a functional distribution map. As indicated the architecture easily allows iteration of the process. Furthermore, output functions can be used to modify state variables, even those used in the original functional determination. This allows for niche and landscape modification in a very similar manner to cellular automata. In this manner very complex simulations can be explored; however the main purpose of this architecture is to provide the informatics capabilities to researchers, technically oriented policy analysts, educators, and other users. Such a system can also allow for combinations of functions, to represent more complex ecosystem services. A conceptual diagram of this is shown in Figure 11.

We hope we have demonstrated the feasibility of building functions into an informatics enterprise using only a slight modification to the existing architecture of Geographic Information Systems. This approach is being developed in several locations, and already there are instances of its effective deployment for limited purposes.

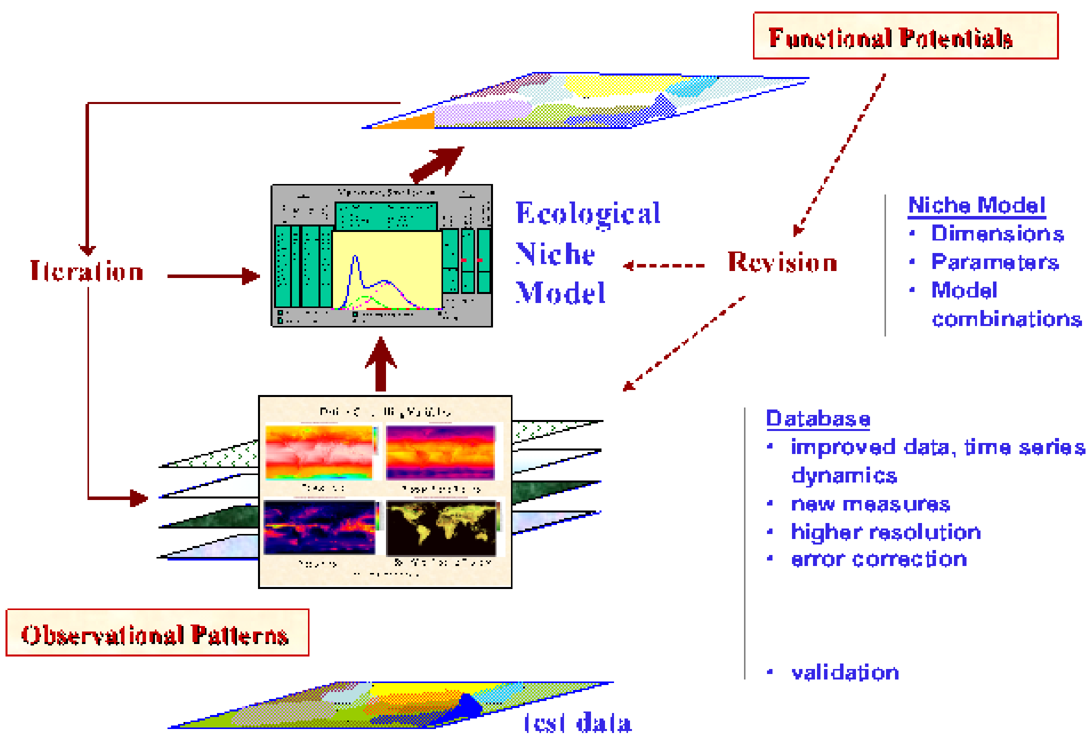


Figure 10: Iterative Use of Niche Model

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End Notes:

[1] There are general implications of relational complexity for science which are beyond the scope of this paper.

[2] This does not mean we believe life can actually be duplicated in a state-based computer. The transformation we made from natural philosophy – the Rosen relationship – to a practical implementation of it in terms of structure-function relations, changes the entailment structure significantly enough to prevent it from being fully natural. In particular, functions affect whole systems, not just their structural aspect. This happens simultaneously in nature, and by this construction we are stretching it out iteratively for analytical purposes. The analysis cannot be reassembled into a synthetic whole because it has been permanently stripped of its simultaneous, holistic entailments. In a sense, the moment of "now" has been removed to make the system observable in pieces, as all analysis does. We do not know how to put "now" back into the system, which is probably the necessary ingredient for actual life. But for informatics, we know that a scientific theory or model is never the actual thing it represents. It seeks to be our best cognitive representation of it.