Relational Complexity in Natural Science and the Design of Ecological Informatics

by

JOHN JAY KINEMAN

B.A., University of California, Los Angeles, 1972

M.S., University of Colorado, Boulder, 1979

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written by John Jay Kineman

has been approved for the Department of Environmental Studies

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Dr. Carol A. Wessman

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Dr. Bela A. Banathy

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Dr. Michael Coughenour

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Dr. Robert Guralnick

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Dr. Roger Pulwarty

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Dr. Daniel Sturgis

____
Dr. Robert Ulanowicz

Date______________________________

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Human advance has come with increasing impact on our natural world, raising questions of ecological health and sustainability and challenging science to provide better ways to manage ecosystems. Implicit in this challenge is a need for better communication. However, meaningful application of environmental and ecological informatics to living systems has been severely limited by historical biases in the definition, design and content of information. In particular, the mechanistic concept of nature objectifies material existence, separating it from formal laws; a program suited only for describing non-living systems. The description of complex living systems requires that we instead objectify whole relationships that have both material and formal aspects. Robert Rosen's theory of relational complexity addresses this problem, providing a new concept of information and nature that is appropriate for complex informatics design. Furthermore, the principle of relational complexity is found to apply generally to nature, such that the principles of mechanism represent a special case. Rosen's discovery introduces a form of analysis appropriate to living, social, and psychological phenomena, with profound implications throughout science and society. Here, the ideas are developed in detail regarding ecological science, policy, and ethics, as comprised in the societal need for better informatics. The approach corrects historically vague definitions of ecological units and terms of reference for ecological theory. Rosen "modeling relations" in nature translate to empirical *structures* and *functions* defined as complementary information relations in local and general systems. Naturally complex relations can be represented in an information system in terms of these units, related mutually by means of generalized niche models. Complex architecture can be articulated on this basis to provide more meaningful communication between science, policy and society. Broader implications extend to the roots of conflict and uncertainty in relation to decision-making. Philosophically, the relational view suggests an integral ethical orientation, and a means to relate human values with science. The fundamentally different ways of viewing nature—mechanism vs. relationship—reflect a similar divide between instrumental views of nature and ethics typical of Western industrial culture, and views of intrinsic order and emergent ethics more typical of traditional Eastern cultures. Just as mechanistic and relational informatics must be combined to properly represent ecosystems, instrumental and intrinsic value beliefs must be combined to address human well-being.

Dedication

To the memory of Dr. Robert Rosen who revealed the deep organization of life; may we realize his insight that, indeed, biology does inform physics.

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Chapter One:

Empirical Foundations of Ecosystem Science and Informatics

Abstract

Many global environmental studies and assessments claim significant human impact on the world's ecosystems and their related goods and services, on which humanity depends. For example, the Millennium Ecosystem Assessment (MA) concluded that nearly all of the world's ecosystems are in serious decline and that we lack basic information needed to understand, monitor, and manage them. Counter-assessments challenge these views and apply different contextual meanings. The ability to reinterpret ecological facts outside their original context is a present shortcoming in ecological informatics that has resulted in a crisis in science itself, where its independent value to policy and society is being seriously questioned. While the idea of whole "ecosystem management" has been adopted in most national and international environmental strategic plans, its theoretical basis and methods remain unclear. These problems can be traced to the legacy of Western scientific thought that is rooted in a physical-mechanical view of nature, which prevents science from meeting the current need for understanding living systems complexity. Environmental science and informatics have had a history of primarily physical systems orientation and inquiry, largely because it was possible to standardize measures in the physical sciences, which in turn allowed the development of advanced instrumentation for data collection. This spawned an era of large scale global science campaigns, central data repositories, and development of informatics

methods that were appropriate for the physical sciences. The ecological sciences were slower to develop and still lack agreement on basic measures (or indicators) of living phenomena. Unlike physical measures, ecological measures circumscribe relationships that are inherently system-dependent and heterogeneously distributed. While some theories and methods for handling such information are emerging with advanced information technologies, we still have not solved basic theoretical problems of what to record or how to synthesize effective information—a shortcoming that impairs our ability to communicate the factors needed to assess ecosystems and to decide policy. The problem can be addressed as a need for theoretical definition of natural functional components in living systems. The MA and related studies' attempts to circumvent this problem by communicating in the terms of ecological economics is also limited by these shortcomings and the inherent reductionism of that language. A complete rethinking of ecological informatics in more foundational ecological terms is needed to allow it to capture and communicate the complex nature of living systems, along with scientifically and ethically grounded alternatives for decision making.

Introduction

The recent centuries in Western industrial society marked a material and computational age in science where precise 'laws of nature' were applied with tremendous success, thereby spawning a technological age. The physically reductive, or mechanistic, view of nature underlying this revolution was so successful that, in essence, it became a secular god (Jeans, 1930). However, partly as a consequence of that success, we are now expanding beyond the limits of what that view can describe, and thus encountering the effects of a more complex reality. Such effects were previously ignored as random chance or error; however, raised from their slumber, they now intrude on everyday experience and demand explanations that neither reductive science nor socio-political construction can provide. For many, we face the dilemma of primitive Man; that seemingly random events increasingly rule our destiny and thus demand explanations; which we will take from whatever source can provide them, rational or not (see: Jung, 1933). We have entered a new age: one of complexity and living phenomena where the tools of the former age are no longer adequate. The cultural impact of this sudden lack of intellectual mastery may seem like falling off a cliff—reality again seems confused and the foundation for making decisions regarding complex systems is in disarray (Pielke, 2002). The result has been greatly increased polarization in science and society (Sunstein, 2002), a symptom of severe psychological dissociation—a split in the collective mind (Jung, 1921; Wilkinson, 2005). This split-mind condition expresses itself in extreme forms of personal and societal polarization, including an apparently increasing social and political divide globally. The situation requires us to find better modes of integral thinking—a continuing search for the 'new paradigm,' but with some urgency. In such considerations it is important to retain the benefits of prior understanding while attempting to advance in new directions. I thus begin with some historical analyses.

I will explore the need for a new integral view of nature and its application to the fields of environmental and ecosystem science from the perspective of *informatics*—the information connection between natural science and society. This is appropriate, I believe, because it is precisely the breakdown of communication in society that the above trends represent. I also believe that ecology is a field that is well situated to provide the new integral view if it can define its own theoretical foundation. Furthermore, while the current polarization of thought and values in post-modern society seems to be evident in virtually every sector, it is perhaps most analytically accessible in regard to the global environment and ecosystem. These associated fields emerge with critical interest because we have now become a global society accessing limited resources. Furthermore, as part of a global society, science is now capable of a much greater study of nature as a whole, focusing on general and growing concerns about feedbacks from human impact as we extract natural goods and services through increasingly efficient and widespread technological means. A brief examination of the status of global ecology and our approach to it in terms of the role of scientific information reveals a great inadequacy at the foundation and core of science. *Ecological informatics*, the essential means of communicating ecological science to society and policy, is hampered, even crippled, by the legacy of reductive methods in physical science and corresponding concepts of information. There is much to learn in this difference between the past, highly successful, *material* orientation to nature and its inadequacy to meet current needs for a *systems* orientation. We will see that this examination leads directly to the problem of living system complexity and to the need for a more adequate theory that neither physical science nor ecology currently offers, to solve the problems of managing complex systems.

The Environmental Debate – What's Missing?

The Assessments

There have been a number of global assessments recently. Their mounting concern is the ability of the world's ecosystems to sustain society in the face of major crises due to loss of resources and changes in ecological function that are accelerated by changes in society. Biodiversity seems to be at risk from shifting species ranges, changing resource availability and other factors. Human-induced stress on ecological goods and services may be cumulative even while many argue that technology and economics have improved the condition of mankind and will continue to do so. It is relatively undisputed that a very strong connection exists between human and natural systems. The debate is therefore about how that connection works, and the clear message is that we really don't know. This lack of basic theory and empirical knowledge allows arbitrary interpretations to be introduced in the public sector, from possibly inappropriate contexts and untested personal beliefs. The resulting polarity of environmental/ecological views thus renders science inert with regard to policy and decision making. This is a very confused situation. The quality that promoted the success of science in the era of mechanistic studies was that it translated all contextual meanings to external laws—the Platonic realm—thus singling out the passive material existence that, to a significant degree, lends itself to precise description. However, we lost sight of the fact that this is a specialized view and we began to think that mechanisms are the general reality. If science cannot now depose this god and embrace a more complete picture of nature, it will have little to offer in the complex thinking that the future demands.

The recent World Summit on Sustainable Development listed "*preserving biodiversity and improving ecosystem management*" among the top five challenges facing mankind in the pursuit of global development (United Nations, 2002). This recommendation followed numerous global assessments (WRI, 2001; Gitay, 2001) (WRI, 2000; UNEP, 2002) that cited a decline in global ecosystem health in terms of goods and services provided to humanity. The first comprehensive globally integrated ecosystem assessment, the four-year Millennium Ecosystem Assessment (MA) (Millennium Ecosystem Assessment Board, 2005; Millennium Ecosystem Assessment, 2002), was inaugurated in 2001 amid mounting concern about the future ability of the world's ecosystems to sustain society. This and prior assessments recognized that the health of ecosystems and their diverse organisms,[1] which underlie all ecological goods and services, is rapidly being destroyed or impoverished by human activity, both directly and through modification of global systems.

The background knowledge that was required for the MA was an understanding of 'normal' vs. current condition of global and regional ecosystems. Ecosystems are defined by close relationships between organisms and between organisms and their environment. Life on Earth is carbon based, and entirely dependent on water. While the largest store of carbon is in the deep ocean and solid Earth, much of that reservoir has been unavailable to living systems until recently, through fossil fuel extraction and emission (from burning) to the climate system.

[1] The term 'biodiversity' refers, technically, to a measure of variation in species types; however the term is also used to refer to the actual suite of organisms that a biodiversity measure would summarize.

Available carbon is distributed between the surface ocean (~900 gigatons), biosphere (~613 gigatons), soils (~1580 gigatons), and atmosphere (~597 gigatons). The IPCC lumps carbon content of vegetation, soil and detritus at 2300 gigatons (Denman et al., 2007: Figure 7.3, pg. 515) The greatest recent change in carbon storage has been atmospheric carbon (CO_2), which rose from 580 to 750 gigatons since the 1800's. The gross natural flux between the atmosphere and terrestrial biosphere is approximately 120 GtC per year, or about 16% of the entire atmospheric reservoir. Variations in that amount have significant effects on atmospheric carbon (and vice versa), and the degree of greenhouse warming, which is primarily caused by CO^2. Fossil fuel emissions have increased the rate of input of carbon to the atmosphere over that of the natural biosphere by about 10% (~6 gigatons/yr). The stabilizing relations of the system are unknown. CO^2 increases may be mitigated by biospheric modifications (such as aforestation, agricultural modifications, etc.), an area of intense current research (Denman et al., 2007).

The most quantitatively important nutrient for life is nitrogen, which accordingly has a major regulatory effect on ecosystem processes. Aside from unavailable stores in the solid Earth, Nitrogen primarily resides in vast stores in the atmosphere and ocean, and is made available to organisms through nitrogen fixing, as part of the nitrogen cycle. According to Socolow (Socolow, 1999), nitrogen cycling involves terrestrial storage of fixed (organically reactive) nitrogen of about 100,000 megatons, of which about 4% is in living organisms and the rest is in dead organic matter; and oceanic storage of about 1 million megatons. He estimated pre-industrial cycling of fixed nitrogen through the biosphere and soils to be about 1200 megatons per year, which is replenished by the nitrogen fixing cycle at a rate of about 140 megatons per year (Vitousek previously estimated 90-130 megatons (Vitousek, 1997). Human enterprise has increased the global nitrogen flux by about 160 megatons per year (Socolow, 1999) likely to increase to 195 megatons per year by 2030 (Vitousek, 1997). About a third to a quarter of this added reactive nitrogen goes directly to the ocean. **Figure I-1** shows the post-industrial rise of global anthropogenic nitrogen inputs, primarily from power plant emissions, vehicle emissions, septic tank leakage, manure overstock runoff, agricultural emissions, fertilizer runoff, wastewater effluent, and food and feed imports (Lambert and Driscoll, 2003). The human input of fixed nitrogen already exceeds the total global fixing rate, and the natural capacity for nitrogen uptake, by two times, thus saturating many systems and "leaking" nitrogen, which eventually ends up in coastal waters via runoff. The effect of an overabundance of organic nitrogen has been to over-drive ecosystems, depleting oxygen (eutrophication) and encouraging outbreaks of sometimes harmful algae and fungus. Major effects include acid rain, acid lakes and streams, ozone and smog, climate change and ozone depletion, nitrogen saturation in forests, over-enrichment of coastal waters, and groundwater contamination Lambert and Driscol, 2003. This excess nitrogen forcing is a likely cause of coastal "Harmful Algal Blooms" that have been

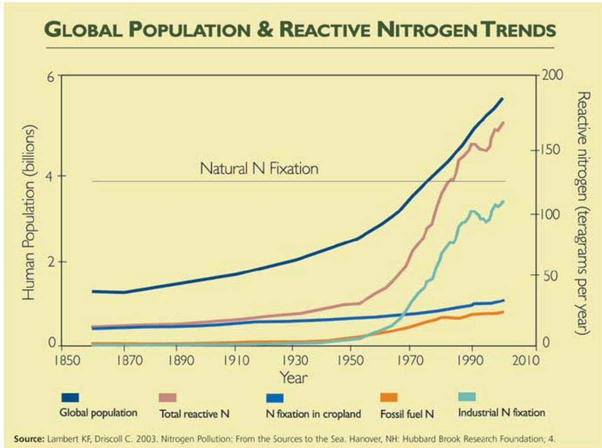

Figure I-1: Human Input of Fixed Nitrogen (Lambert and Driscoll, 2003) increasing world-wide, damaging fisheries and raising serious policy and management concerns (Perciasepe, 1997).

Aside from these obvious feedbacks between ecosystems and biogeochemical cycles, it is generally understood that living systems have many feedbacks with their physical environment. We have discovered that the Earth's biosphere has historically had a significant role in determining the condition of the Earth's physical environment. The most obvious example is the atmosphere itself, which is maintained far from chemical equilibrium by the biosphere (Lovelock and Margulis, 1974). We know that ecosystems play a significant role in modulating the climate system through global biogeochemical cycles (Vitousek, 1994). The primary global systems involved in sustaining life and providing ecological goods and services to humanity (Costanza et al., 1997) are all being significantly modified by human action (Vitousek et al., 1997). We do not yet understand the self-stabilizing capacity of ecosystems, except that catastrophic change to entirely different conditions is possible—a behavior typical of complex systems. Relationships recently coming to light include the significant effect of deforestation and land conversion on regional climate (Cooley et al., 2005), the effect of land clearing on carbon and nitrogen budgets (Vitousek et al., 1997), and the effect of human impact on primary productivity (Roy, Saugier, and Mooney, 2001). Changes in productivity alter the fluxes to and from various sources as well as the sinks in the biosphere and physical systems. Some of these fluxes are buffered in the ocean and biomass, making the consequences of change cumulative and delayed. The biosphere has other feedbacks to physical systems, affecting, for example, heat budgets, atmospheric and oceanic circulation patterns, ice storage and melt, ocean salinity, temperature, rainfall, humidity, storm tracks and energy, biogeochemical storage, amount of sunlight, seasonality, etc.

Human activity and its presumed impact on ecosystems has greatly increased since the industrial revolution because of population growth, industrial and technological development, and social value changes toward greater production and consumption (Turner, 1990). According to the MA, in the last half-century major changes in the environment and ecosystems have occurred at all scales with global degradation in approximately 2/3 of all ecological services, *"running down natural capital assets"* and creating *"a significant barrier to achieving the Millennium Development Goals to reduce poverty, hunger, and disease."* The MA reports this decline across most systems and sectors from direct human impacts, such as land conversion, over-harvesting of natural systems, water extraction, agriculture, forestry, aquaculture and other resource use practices that are considered unsustainable; and from indirect alterations that are unintended consequences of human activity and its outputs. The MA attempted to document these changes in terms of specific measures of change. Major effects were grouped into five major categories: nitrogen loading, atmospheric chemicals from industry, water pollution, habitat loss/fragmentation, and climate change. This and similar studies present the following picture: The CO^2 concentration in the atmosphere has increased by 70% because of human inputs (Schimel and et al , 2001), and is still rising. 10-15% of the species on Earth have been driven to extinction by land clearing and commercial harvesting (Vitousek et al., 1997) and 25% of the remaining biodiversity is threatened in what is currently the highest rate of species loss of the six global extinction events known in Earth's history. These losses include sharp declines in commercial fish stocks, mostly from over fishing. Agricultural expansion, deforestation, and other land use changes have converted between 35-50% of the usable land surface of the Earth from its prior condition and function (with 25% under cultivation) (Vitousek et al., 1997). Nitrogen fixation from manufactured fertilizers and deposition into the soil and water has more than doubled the natural flux of nitrogen into the biosphere, enhancing commercial agricultural production but exceeding the ecological capacity to consume the excess. This has led to extensive degeneration of aquatic and coastal ecosystems as nitrogen saturation produces hypoxia and eutrophication. Species and functional changes, as well as “dead zones” and “harmful algal blooms” are the results of these enhanced inputs compounded by other system changes (Matson, Lohse, and Hall, 2002; Vitousek et al., 1984). The world’s highly productive major deltas appear to be at risk of serious land loss because of climate and hydrological change (Huh and Coleman, 2004) (Christian et al., 2005), as 90% of the major rivers are now dammed and their waters diverted such that many large rivers (e.g., the Nile and Colorado) at times no longer reach the sea (Nilsson, Reidy, and Dynesius, 2005). The MA claims that today there is not a single ecosystem, except at the poles and deep ocean, that has not been significantly degraded by human activity (Millennium Ecosystem Assessment Board, 2005).

Current estimates from the MA and other assessments are that the human population has more than doubled since the 1950’s, with even greater increases in the use of resources and the production of waste and other pollutants because of rising per-capita consumption. The MA reports that 2 billion people are vulnerable to diminishing fresh water supplies. As developing countries seek to achieve the prosperity of the industrialized world, consumption rates and human impact are further accelerating. Chapter One Supplement provides excerpts from the major findings of four recent assessments: The Millennium Ecosystem Assessment (Millennium Ecosystem Assessment Board, 2005); UNEP's third Global Environmental Outlook (UNEP, 2002) which summarized trends since the first UN Summit on Sustainable Development (the Stockholm Conference); the Intergovernmental Panel on Climate Change (Denman et al., 2007); and the World Resources Institute's Pilot Assessment of Global Ecosystems (WRI, 2000). Many believe that environmental disruption, global fears over securing energy and other resources, economic disparity, and so forth, are the causes for political and economic disruption as well as environmental degradation; and that the reverse is also true—that ecosystem degradation has throughout history been a cause of major social upheaval, and that we are seeing, for example in catastrophic drought in northeastern Africa, some of the first of upcoming major conflicts as a result of climate change. The picture these assessments present us is that we are possibly sitting on a number of ecologically mediated time bombs.

The Counter-Assessment

Despite considerable agreement among these assessments, their message of warning for humanity has nevertheless been challenged in the public and political arenas. A counter-assessment prepared by Bjorn Lomborg (Lomborg, 2001) chronicled a history of continuous advance in human prosperity in all economic sectors, including rich and poor. He wrote: "*Mankind's lot has actually improved in* *terms of practically every measurable indicator.*” This alternative view represented an ideological backlash against the “*apocalyptic*” warnings of the major environmental assessments and their “*litany*” of “*gloom and doom,*” of which Lomborg stated: “*There is just one problem: it does not seem to be backed up by the available evidence.*” Lomborg claimed that all of these assessments misinterpret the trends and overlook measures of human prosperity that have been steadily rising, such as per-capita income, technological advances, agricultural productivity, alleviation of poverty, Gross National Product, and others. He argued that the future of humanity in the hands of technological advancement and globalization is “*the best of all possible worlds.*” He dismissed the argument that there may be any hidden natural cost to this advance and claimed that economic growth and financial cost-benefit will continue to correct or counteract environmental and ecological problems and ensure a bright future for our next generations. He cited many trends to support his claims—perhaps as many as cited in the ecosystem assessments—but primarily in terms of economic and technological measures. He attributed systematic improvement in the human condition—a defensible thesis—to the industrial/technological revolution.

However, he dismissed costs of this advance in terms of natural capital as unsubstantiated. The idea of depletion of resources, both renewable and non-renewable, and limits to growth, were generally characterized and dismissed as myth. Regarding global warming, Lomborg wrote “*We need to separate hyperbole from realities in order to choose our future optimally*” (Lomborg, 2001). He cited lack of adequate knowledge to determine if the impact of CO^2 doubling—which he did not dispute—will result in a 4.5ºC increase or a "*small*" 1.5ºC increase. Global scientists say that even a 1.5ºC increase globally will have significant effects on ecosystems and biodiversity, if not also "tipping" non-linear physical systems (such as the stability of ice fields) to a different stable mode. The MA stated, for example (see Chapter One Supplement), that today's temperature, which has increased by approximately .7ºC in the last century, has already had significant effects on biodiversity.

Lomborg attributed much of the environmental concern to "*data massage*" by scientists with a bias—or "*torturing the data until they speak*" (Lomborg, 2001). One could make the same claim in return. For example, in one section he claimed that the use of "ppp" dollars—i.e., monetary units that measure the purchasing power corrected for within-country economies—is the appropriate way to compare equity and inequity of wealth (in which view the trend is slightly improving); whereas throughout his book he argued for globalization and lifting of trade barriers. He thus showed us that a Somalian's purchasing power of Somalian goods has improved from its own past (albeit at a level about 100 times less than in America, and losing ground), and cited this as an example of a general global improvement for all countries. He did not show us how much of Somalia a typical American could buy or how little of America a typical Somalian can buy, or how dramatically this disparity is skyrocketing. But he did argue that removing trade restrictions and globalizing financial markets—which would make the disparity between nations all the more noticeable—is the key to continued prosperity "*of this sort*." Clearly the difference is in how prosperity is measured and what costs are considered, but also what *sort* of prosperity one is concerned with; prosperity for the already prosperous or some progress in closing the gap in well-being between rich and poor. Lomborg claimed that economic and political stability will solve the environmental problems, but another possibility is that it will worsen them; his argument was based primarily on faith in historical trends. For example, he did not consider how unregulated financial markets will feed back to environmental or ecological management. Lomborg had little difficulty making a straw man of the *"environmental litany"* (as he called it) citing exaggerated and unsupported claims about ecological decline; however, he replaced it with a different 'litany' of laissez-faire capitalism and technological development, with most values being reducible to bottom-line economics, in the controlling hands of a minority.

Are We Pushing the Limits?

During the recent period of industrial expansion, growth in many sectors of human development has proceeded at linear to exponential rates (Noble and Costa, 1999; Vitousek et al., 1997; Turner, 1990). Mathematically, exponential growth eventually exceeds all practical limits. We are used to continual growth because we have been far from these limits until recently. But monitory growth, necessary to pay the cost of maintaining the general system, must, on the average, be matched with growth in actual goods and services. Problems arise because for a while this ultimate accounting can be put off, and good fortune can bring in new resources. The economic system decouples buying power from resource accounting, allowing a considerable margin for enterprise and luck to catch things up. Until that balance is restored, however, there may be increased competition for limited goods. The global economic system, predicated on growth, is a way of mortgaging natural capital to leverage creativity, and it has been a successful formula baring corruption or natural calamity. Clearly, however, ecological sustainability cannot be achieved with finite resources and exponential growth of consumption. Economic growth is predicated on and demands an expanding resource base. Only so much of that expansion can be gained through greater efficiency and discovery. New, more productive technology is thus required, pushing us closer to a more vulnerable extreme. Even linear growth requires an expanding resource base, and thus has a definite time limit if resources are finite. The system may be self-regulating or regulation may be required, but unlimited growth may not be an option while confined to Earth. As we reach the maximum utilization limits of some of Earth's resources, growth rates associated with human development (including economic growth) should be reconciled with the need to stabilize use of natural capital at ecologically sustainable levels. Even advances in technology that allow these levels to be increased must reach an ecological optimum, and at this stage we should realize that we have created a highly optimized and highly specialized relationship that is even more vulnerable to disruption because it has little room for compensation (McMichael and Powles, 1999). We seem to be operating on the assumption of luck.

Many scientists now predict that growth will have to reverse in the near future. McMichael and Powles (above reference) projected a sharp peak and turnaround of per-capita energy use around 2012. The Odum brothers projected a similar turnaround and considered the tendency of systems, when forced out of equilibrium, to "overshoot" when returning to balance, perhaps deepening a possible crisis in proportion to the degree by which it is delayed by artificial subsidies, for example by continued oil extraction (Odum and Odum, 2001). While sustained human and economic growth is mathematically impossible in a finite domain, it remains a political ideal and widely-held goal among public leaders (Bookchin, 1989). It would be a rare politician who could survive today on a platform of limited or negative growth. It is thus within this social context of unlimited development goals, expanding resource use, and rate-limited ecological systems that science is asked to better inform policy. Not surprisingly, the rise of an ecosystem perspective in the strongly industrialized countries has been slow. However, it is growing today out of mounting fears that we are nearing a global crisis, or perhaps less reactively, out of recognition that our future interactions with nature will need to be increasingly managed.

Still, ecology is perceived by many as pessimistic and at odds with human desires. Voices citing the history of human conquest of nature as evidence of unbridled prosperity ahead may have greater political and economic strength than those of environmentalists, who appear fearful and limited in creative outlook. Because of our collective dependency (some would say addiction) to better and better living in material terms, there seems also to be a cloud of denial about possible consequences. Indeed, ignorance can, for a while, induce self-reinforcing trends, but as with global economics the bubble must eventually burst as the external reality comes crashing in on an artificial belief system. The question, then, is how long can this belief in unlimited growth drive humans and nature to perform accordingly? Despite Lomborg’s claims that prosperity has been on the rise throughout history as a general trend, we have numerous repeated examples of how human excess led to collapse. Are these just fluctuations on a steadily rising curve, or are they examples of a larger principle of balance that we should learn?

Does Science Really Matter?

The difference in views in the above debate has been incorrectly framed by those advocating the power of technology, as an issue of accepting change. Environmentalists are often characterized as unwilling to embrace change and creative enterprise. Clements, however, wrote:

> *"It is simply an ordinary feature of subsystems that stasis is not indefinitely maintained and that, therefore, major and highly significant change occurs in biotic systems leading to both value and disvalue from a human point of view. However, change itself, I contend, is both inevitable in most systems and on the whole desirable."* (Clements, 1995)

But the disagreement is not about acceptance of change; it is about understanding, and perhaps co-creating, the meaning of change; one group deferring to an inferred natural order, the other to an instrumental human order. It is an argument about values.

It is entirely possible that, within an acceptable range of error, both accounts of the state of the world presented above are factually correct. With 2,930 footnotes that reference 70 pages of literature citations, Lomborg's book is as well documented as any environmental assessment. It is perhaps the clearest evidence that data, by itself, can be selected and interpreted to support opposite ethical and policy positions. The difference in views thus lies in the semantics—the meaning each group assigns to the trends and projections that the facts reveal, and the human meanings that establish which facts to consider. Each side of this debate defers to science, albeit selectively, to establish a structure of conditions and projections. Each side then adds their own meanings. The debate becomes one about values and life style, topics that traditional science has been unable to comment on.

This debate, which continues today, is about the interaction between two complex systems—nature and human affairs, each with very different internal functions. If we know anything about this kind of interaction, we know the result is highly uncertain and that causal relations are hard to factor. In the environmental assessments there may be too little consideration of advanced scientific and technological solutions, or natural corrective feedback in the ecosystem. In Lomborg's assessment there may be too little consideration given to natural capital, or to the question of ecological sustainability and the characteristic of complex systems to "flip" from one state to another. One view is concerned about ecological sustainability, the other about economic sustainability. But can either actually be assessed or managed?

Like the concept of "security," it is often only the opposite of such concepts that can be defined and managed if conditions reach the level of crisis. Like 'security,' sustainability, in economic or ecological terms, is a goal based on some level of comfort and acceptance of risk. The practical measure of sustainability is some form of risk assessment (NAS, 1993). So, the debate is really over the ethics and values that form the terms of acceptable risk, a discussion in which facts are often 'spun' with different meanings because of one's assumptions and goals. It is valid, for example, to claim that estimates of species loss are based on little more than speculation; but this is because we do not have data on perhaps 80% of the global biodiversity, whereas the rest is clearly on a downward spiral. The message of those who use such inappropriate statistical argument to claim lack of knowledge, is not that biodiversity is doing well, but that we should assume so unless overwhelming evidence is presented to the contrary. The opposite ethical argument is that some concept of precaution should be applied. Both are value judgments requiring that the values and risks be defined.

Similarly, facts we do have can be given different meanings. We can, for example, document that our technological and economic revolution is a human experiment that has been running for only a small portion of human history. This can be compared to a scale of millions of years required for selection and adaptation of "fit" natural systems. One might interpret this to suggest caution in modifying nature, considering that a million years of natural balance should produce a more sustainable result than 200 years of human ingenuity. But that is a semantic[2] addition to the data, and as discussed in Chapter Two we tend, perhaps inappropriately, to think semantic conclusions cannot be part of science, regardless of how much empirical work has gone into producing them. It is also possible, as Lomborg demonstrated, to take the opposite semantic view and cite our great success in only a few centuries, as evidence of the miracle power of technology that can far outstrip the slow pace of evolution in finding solutions.

[2] The proper term is actually "hermeneutic" referring to the general application and interpretation of meaning, however I use the more popular term 'semantic' as a linguistic analogy that is popular in the complexity literature, which often refers to the dichotomy between syntax and semantics.

This ability to freely apply facts abstracted from one semantic context (nature and natural science) to very different post-scientific contexts (social, ethical, and political) has led some policy analysts to conclude that science is inert or even enslaved by political spin (Sarewitz, 1996). The claim is that science can be twisted to fit virtually any political position with at least enough controversy or emotional appeal to make the case plausible in a public context. How do we solve the problem of attaching proper meaning to science? Some analysts conclude that we are wasting our money on basic science; that we should adopt the belief that science is policy driven and accordingly frame (and fund) scientific questions around decision needs (Pielke Jr. and Byerly Jr, 1998; Murray, 2005). This suggests that the future of science funding, aside from corporate science, may eventually resemble political campaign funding, for it is well-known among philosophers that the greatest biases in science do not come from falsifying or misrepresenting data, or even from equivocation between contexts (spinning the meaning, which at some level may be correctable), but even more strongly and subtly from selectively framing the questions. A shift away from basic science funding toward driving science by policy needs might signal a headlong leap in the direction of more arbitrary bias and political control. These boundaries are already being severely tested by political appointees who may increase political control of government funded science (Fitzsimmons, 1999).

Aside from funding biases, if we want science to matter in this debate, more is required of it than to present data and make statistical estimates; it should provide solid theory for meaningful interpretation that is not so subject to post-hoc spin.

Knowledge of natural behaviors in context is needed to interpret the meaning of facts. The immediate crisis suggested by the environmental debate is nothing less than a crisis in science itself. It seems apparent in public policy, education, science funding, and highly fragmented government programs that science about the living world is in disarray and either heading for, or already in, the status of a train wreck. The assessments and current policy studies indicate that science has lost its authority and ability to communicate relevant information about living systems, and non-scientists feel increasingly qualified to substitute almost any context in its place. This situation must be averted if the extreme polarities that have resulted in politics, science, and society are to be healed.

The Missing Semantics

The lack of a strong theoretical foundation and clear empirical elements in ecosystem science, compounded by failed attempts to make the physical perspective work for ecology (Platt, 1964), has led to confusion and disappointment in the discipline (Simberloff, 1981). Fields like biogeography are constantly searching for new thinking and a rigorous foundation (Bowman, 1998; Crisci, 2001; Huston, 2002; O'Connor, 2002; Grief, 2003; Heaney, 2007). Even with physics loosening its early deterministic grip on reality as a result of quantum discoveries, theoretical ecology has remained obedient to the mechanistic view of nature. Ulanowicz argues, after Rosen (Rosen, 1985a; Rosen, 1991b) that ecology should allow for additional forms of causality, other than the ones traditionally included in the physical/material concept (Ulanowicz, 1997). These additional causalities are the discarded *"formal"* and *"final"* causes in Aristotle's four causal types (Kineman, 2003a).

Arguments based only on measurable fact alone carry inappropriate weight in Western industrial society because we have been taught that subjective meanings should be stripped away to reveal what is otherwise repeatable and thus 'scientifically' true. This philosophy applies to only a very special kind of science—physical and positivistic. Often missed in defense of such science is the assumption that the scientist can add back the missing semantics later, from knowledge of the laws of that discipline. That has worked in physical science because there are indeed general laws for physical systems. It is far less true in ecological and social science because the laws of living phenomena have strong system dependencies and are therefore not general laws of the universe that can be commonly referenced (see Chapter Two)

If we cannot verify an expert's re-application of semantic interpretation, then science itself should study and record the semantics at an earlier stage. This means recording much more than measurements alone. We should consider behaviors and meanings (in terms of functions) in the original context of observation and experiment. If we do not study and record these in their natural context, then scientists, politicians, and other people will substitute their own interpretations, from arbitrary life experiences. This seems to be the main problem in the science-policy communication debate today.

For example, one who spends a lifetime in the forest learns to sense and respect the ways of nature, perceiving in more intuitive ways how it functions and what it means in context and perhaps to humanity through different interactions. But perhaps equally, one who spends a life on Wall Street begins to experience and respect the forces of economics and workings of human enterprise, and to sense these meanings as if they were natural, which indeed they are in that context. It is from these personal relationships that we derive our view of the world and its values to us, which can then be easily added to data if it has previously been semantically sterilized (Bunnell, 2000). Interpretations are more valid when related to their original contexts, and thus we need methods to retain contextual relations.

In ecology it is common to refer to "structure" and "function" of a living system somewhat loosely, but implying the idea of complementary aspects of empirical study that point us toward a natural (ontological) whole. However, they do not do so independently, meaning that if they are separately recorded, they are automatically taken out of their natural context—the larger system in which they are fundamentally related. The implicit whole that was originally the subject of study is thus lost and cannot be re-constructed later from the epistemological elements. In contrast, such a procedure is indeed valid for describing a mechanical system (Rosen, 1991a), because in that case the functions are *defined* as general from the outset (Chapter Two). Thus, in the case of living systems, we must preserve as much of that whole as possible in order to communicate meaningfully. If life science does not communicate contextual meanings, then we will automatically draw upon our general conceptions to fill in the gap. This method can describe nature only to the degree that human functional assumptions are informed by intrinsic natural ones, taking us then full circle to an analysis in which, in that case, human functions should be considered natural. Thus where the mechanistic world view based on general physical laws does not work, that is, for complex living systems, we should instead have a view where we can record non-general functions (ecological 'laws'). These should not be thought of only in the sense of physical processes, but as contextual semantic influences that induce system change.

This conclusion bears directly on the assessments; how we understand them and how we might improve them. The two views of the state of the world discussed above represent different semantic interpretations of a factual syntax[3] —overlapping sets of facts and trends stripped of their natural contextual meanings by a positivistic legacy in science that purposely removes semantics from observations. When semantics are re-applied from general laws, they will support the material view and corresponding values. When this obviously misses the important questions of life and complexity, semantics are drawn from everyday life and social construction. As long as this ethic is maintained and reinforced, as it currently is, there can be nothing remaining in the data itself to suggest the proper meanings to apply in its interpretation. This fact of logic was the main flaw in positivistic science and it should be clearly understood if we are to comprehend living systems.

A brief history of global science informatics will demonstrate that this problem has pervaded the history of environmental science and informatics, leading to under-representation of ecological data because of its reduction to physical measures. This has led to further disappointment when these data, thus lacking proper semantic and contextual referents, cannot be used to answer ecosystem questions.

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[3] Syntax in a natural sense is analogous to its use in language—it refers to the structure of the language, or in the case of natural language as analogy, it refers to the material pattern. Semantics refers to the meanings of structure or pattern, either ontologenetically (potential patterns) or once a pattern as been defined and is active in a subsequent context.

Physical Roots of Eco-Informatics

There are deep historical and epistemological reasons for the divide between hard scientific ‘fact’ and ‘soft’ scientific meaning, the latter often being excluded or marginalized in science communication. A physical orientation to nature whereby intrinsic semantics could be ignored, to the disadvantages discussed above, has strongly characterized our global data and information enterprises since their beginnings.

The International Geophysical Year (IGY, 1957-1958) was considered a highly visionary program at the time—to explore all the Earth’s major regions from the Sun to the Center of the Earth (Berkner, 1957). It was envisioned as the first truly integrated study of the Earth. The real impetus for the IGY, however, is clearly stated in the literature of that time: the emergence of a general observing strategy and the corresponding new technology that developed between the 1930’s and 1950’s; from gravimeters and magnetometers, to remote sensing capabilities at the dawn of the “rocket” era. The ability to agree on commonly useful measures was certainly the most critical factor, for that was what allowed corresponding technology to develop. The availability of technology then formed the basis for launching IGY’s national and international scientific campaigns. Data from those campaigns were clearly specified and of long-term value, justifying the establishment of centralized data archive and stewardship facilities—the International Council of Scientific Unions (ICSU) World Data Centers (WDCs) and corresponding national data centers, which endure today.

However, the opportunity for achieving a unified observing strategy and the technological capability to do so existed almost exclusively in the physical sciences.

Thus, while the IGY attempted to incorporate biological disciplines where possible (most notably in the Antarctica program (Eklund and Beckman, 1963)), neither ecology nor sociology were officially part of the IGY. In retrospect, the IGY was only a first step, taken with the strong disciplinary focus on the physical sciences characteristic of that time. Despite numerous subsequent international programs designed to address the case of living systems (**Table I-1**), the assumptions of the IGY became the enduring legacy of the national and international data centers for decades. The surprising fact is that no explicitly biological data centers were created as a result of three decades of international biological programs despite pressing needs for integrated physical, ecological, and societal assessments and other global system studies. Instead, the traditional physically oriented data centers have each

- IBP (1965-1975) - International Biological Program: ICSU, 58 countries; Ecosystem research agenda; Established Ecological Reserves for long-term protection and research
- MAB (1970-present) - Man and the Biosphere Program: Intergovermental, 138 countries, 14 US agencies, including NOAA; Problem driven agenda: Established 352 Biosphere Reserves for long-term protection and research.
- IGBP (1986 – present) - International Geopsphere-Biosphere Program (in the USA, Earth System Science Program): International, national, and inter-governmental; Began as a physical study of climate change; added ecology (BAHC – Biospheric Aspects of the Hydrological Cycle; GCTE – Global Change and Terrestrial Ecology) around 1990.
- IHDP (1990 – present) - International Human Dimensions (of Global Change) Program: International; To represent the social sciences, which were largely left out of IGBP.
- ILTER (1993-present) - International Long-Term Ecological Research Program: Initiative of US/NSF LTER, established in 1980. Sets aside natural areas for research.
- IBOY (2001-2002) - International Biodiversity Observation Year: Sponsored by DIVERSITAS, IUBS, SCOPE, UNESCO, ICSU, IGBP, and IUMS. *"The IBOY is inspired by the International Geophysical Year of 1957-1958, in which scientists worked together across disciplinary and national boundaries to advance knowledge about the Earth, oceans and atmosphere." (Earth Times, Jan 2001)*
- MEA (2001-2004) - Millennium Ecosystem Assessment: Endorsed by 22 academies and international organizations; Comprehensive assessment of ecosystem health and sustainability of goods and services.

Table I-1: International Biological Science Programs since the IGY acquired (and competed over) various pieces of emerging ecosystem informatics needs, doing them poorly by adopting the methods of the past.

In any given field, a unified observing strategy depends on the ability to generalize in terms of basic measures. Ecosystem ecology itself was only being defined in the 1950's to 1960's, and it was just 20 years earlier that the concept of the "ecosystem" was itself first proposed. Milestones in the development of ecosystem science and management up to modern times are shown in **Table I-2**. The intense peer pressure of a physicalist world view, combined with the inherent complexities that prevent that view from fully applying to living systems, meant failure to establish a unified observing strategy for ecology. Even "Earth System Science" began with a strong orientation toward physical science, introducing the idea of "system," but nevertheless aiming for a physical concept of an ecosystem.

1935	The term "Ecosystem" is coined (Tansley, 1935)
1953-	"Ecosystem Ecology" (Odum, 1953)
1962	"General System Theory"(Von Bertalanfy, 1968) "Systems Ecology" and "Ecological Engineering" (Odum, 1962)
1967-	"Ecosystem Management" is defined as a new view for resource management. (Schultz, 1995; Reid, 2000)
1978-	"Adaptive Management" (Holling, 1978)
1979-	"Ecosystem complexity" and information (network) theory (Ulanowicz and Abarca-Arenas, 1997)
1984-	"Landscape Ecology" arises (Forman, 1995; Risser, 1987; Risser, Karr, and Forman, 1984)
1991-	Ecosystem complexity and "The Ecosystem Approach" (Kay et al., 1999; Allen and Hoekstra, 1987; Holling, 1986; Waltner-Toews, 2004; Ulanowicz, 1997)
1992-	Ecosystem Management is adopted as official policy in the United States Bureau of Land Management (Keiter, 1996)

Table I-2: Milestones in the Development of Ecosystem Science and Management

Each living system has unique properties and thus unique observing requirements, hindering the development of common measures, observing technology, and a common approach to informatics. Whereas physical data can be centralized and standardized because of its reducibility, ecological data are fundamentally irreducible (even what constitutes a species involves considerable subjectivity), and remain correspondingly diverse, system-specific, disaggregated, and widely distributed. It was no mere coincidence that agreement to create a World Data Center for Biodiversity and Ecology came after the establishment of distributed information technology, and that it has been proposed as the first truly distributed data center. Internet technology was just the innovation needed to aggregate distributed and unique resources.

The Internet is a complex system (because it networks both observations and observers) that is capable of representing information across multiple scales and perspectives. Whereas ecology and social science may never find generally reducible quantities comparable to those in the physical sciences, the combination of complex information technology and the development of a full range of ecological and social indicators that span both scale and value dimensions may now chart the way toward a new era of ecological informatics.

The enduring dominance of the physical perspective in global science had two major roots. The first was a kind of "founder effect" that occurred where geophysical science disciplines became established because it was easiest to specify observations for them and to develop technology for them. The second was a much deeper bias in science toward the physical/mechanical view of nature and reality that corresponded with the classical view in physics. It is this deeper root that has proven the most difficult to overcome.

The physical bias of global science and data is thus a legacy of the 1950's science campaigns, but also two centuries of mechanistic philosophy. It remains strongly entrenched in today's institutions and thinking, as is clear in funding priorities and in the inability of the existing data center structures to comprehend, let alone accommodate, rapidly accumulating needs for socio-ecological information to monitor, understand, forecast, assess, and manage critical resources that are being altered in complex ways. The early promise of "system science" brought us quickly to the hope of "ecosystem management," however it still begs for an underlying science of macro-systems that is truly ecological (Brown, 1995). A brief excursion into personal experience[4] of how these biases affected the institutional world of informatics may help the reader to understand the scope and depth of this problem.

National Data Centers

Due to the origins and conceptual constraints discussed above, many of our environmental data and information systems developed in the past several decades have been unable to evolve past a reductionistic model, except in very tentative and cumbersome ways. The same has been true for data management practices, for example in the NOAA National Data Centers. Compared to the primary mission components of NOAA, the data Centers were the slowest to adopt new technologies needed for integrated science. These tools were developed primarily in the ecological sciences to meet the rising demands of complexity, especially for integrating and mapping environmental and ecological data, and for capturing metadata. They were seen, from the perspective of the physical scientist, as unnecessarily complex—a

[4] Personal experience of the author, 1986-2005

correct assessment if one is concerned only with physical data. Technologies or practices strongly resisted included: Geographic Information Systems (GIS) and their analytical components, metadata systems aimed at documenting scientific and methodological context (essential for the interpretation of ecological data or societal impacts), and network/partnership infrastructures necessary for designing and collecting ecological data. Despite successful demonstrations of these approaches and their need in global science, including a highly favorable peer review with 34 responses from the global science community, attitudes were unchanged (Kineman, 1994). In 2003 a National Academy of Science review was sharply critical of the National Geophysical Data Center's traditional disciplinary approach, making strong recommendations to re-orient many aspects of Center operations to a new *"integrated environmental science"* mission (National Research Council, 2003). The report recommended that the Center correct its weak mission alignment within NOAA by re-orienting to *"become a focus within NOAA for 'integrated environmental science'"* including then current ecosystem data programs. To do this, the NAS stated that: *"NGDC should articulate a vision for the future that integrates the disciplines across its broad environmental roles..."* but that achieving that vision would require *"breaking down the walls between the divisions and focusing more on cross-disciplinary activities."*

But these and other efforts and recommendations from the scientific community were ineffective in changing the traditional beliefs and practices; reductionism, reinforced by institutional culture and poor integration with the agency's scientific mission, acted almost like a drug, justifying simplicity for its own sake, at the cost of relevance to pressing agency, national and international priorities. The generation and management of metadata were treated as a bureaucratic annoyance rather than recognizing its necessity for conveying the meaning of system-dependent information. The advance of GIS was resisted until it became the norm for geoscience data, but even then its use was not for integrating data or creating new products, but for marketing data in new formats. The role of these Centers was not perceived as creating new products, but warehousing and delivering "raw" data—a concept only suited for the physical sciences. As a result of these entrenched attitudes, the new informatics had to find new homes, for example in four new NOAA Centers for information integration established since 1993, with only limited partnering with the data Centers. As these trends continued, instead of meeting the scientific needs for integrated datasets, data were particularized as much as possible to boost the official numbers of data holdings—a result of performance measures that, again because of a material mindset, were reduced to essentially meaningless counting of bits. Ecosystem applications were encouraged because of recognized national priorities, but to use for promoting the assemblage of physical data, sometimes under new labels advertising data for integrated science. Given both Agency and National priorities that were strongly articulated over many years favoring an integral perspective, one is compelled to ask: why was this advice ignored?

Simply put, integral approaches and opportunities were sacrificed for marketing "parts" rather than "wholes;" because that was the safest path scientifically, institutionally, and economically. These decisions also reflected a general institutional bias (throughout government) for quantitative measures of performance—reducing value to a numerical measure for accounting purposes. In this way, the reductive, physical bias that permeates the actual informatics was also an institutional and cultural phenomenon. The application of this thinking to every sector of operations and strategy was, in fact, justified by the greater incentives to fit the institutional and cultural system, than those to meet the need for describing natural systems, whether the principles were understood or not.

I present this history as an empirical case study in the power and effect of reductive thinking on the design of informatics in our real-world institutions. In a reductive view of the world, everything, including living systems, can in theory be described in terms of physical variables and general laws. Everything can thus be taken apart conceptually: pieces of 'information' can be distributed individually and re-assembled later. The extent to which this atomism was applied to *everything*, not just the data, is surprising. Data centers were originally responsible for delivering raw observations and nothing more, because they were presumed to be the most reduced components of information. Exceeding that mandate instinctively meant straying from their mission, despite many wise recommendations to the contrary. Also in that view, information content can be measured in data volume alone, providing a very easy measure of success (bits). The idea that an analytical or synthetic product could contain more information than the elements from which it was constructed—that important information about whole systems organization exists at synthetic levels above that of individual measures—was, in essence, a heresy. These trends tended to be reinforced by the fact that we design information systems from the bottom up, relying almost exclusively on reducible and constructible components, accepting the ‘building block’ model from physics.

A major result of this inertia in the face of rapidly changing needs has been to create the current crisis in scientific relevance. In this author’s opinion, the entire data Center concept sits in a very precarious position today, as a result of its inability to modernize. A complete restructuring , or else wholesale replacement, to effect better integration with science is needed as we move into an era of ecosystem science, management, and policy support.

The New Paradigm of Ecosystem Management

The MA recommended taking a multi-disciplinary perspective and establishing new kinds of data and information to build and solidify the empirical basis of assessment and monitoring. Indeed, a new approach is emerging: “the ecosystem perspective.” (Kay, 1994; Kay et al., 1999; Salwaser, 1999)] This has become expressed in national programs as a shift to “ecosystem management.” However, it has been only since the early 1990’s that science has begun to consider ecosystems as units of management and thus units of scientific study.

Ecosystem management became official policy first in the US Bureau of Land Management in 1992 and was quickly adopted by all of the other agencies with a living system mission. Prior to this was a history of attempting to manage biological resources from the bottom-up. **Table I-3** shows the hierarchy of concepts through which biological and ecological management have progressed. Evidently, we were thinking first and most in terms of the ‘parts’ of the system, imagining they could be managed separately from the whole, as in a physical system. We can trace the development of living system management through each of these stages as management failure at a lower level forced consideration of a higher one. Attention thus progressed from biological products, to populations, to species, to habitats, to environments, and finally to ecosystems. There is one more level that we should recognize, which is the level of the general complex system from which we can better understand the true nature of both physical and living systems (Kineman, 2007).

Hierarchical Concept	**Management Approach**
Ecosystem	ecosystem management
Environment	environmental science
Habitat	habitat protection
Species	trophic relationships
Population	growth & carrying capacity
Individual (organism)	markets & bio-products

Table I-3: Hierarchical Development of Ecological Management Approaches

Driven by failure and desperate need to grasp new concepts, this progression to ecosystem management was not led by methodological or theoretical discoveries. It made some discoveries out of necessity, but largely the field remains un-integrated. We arrived at each stage with only the tools of the previous stage, and not the information pertinent to higher levels.

If the global assessments are factually correct, dramatic changes have taken place in the ecology of the Earth during the past 60 years, a period of intense human development involving a large increase in energy conversion, land conversion, and resource use. In this same period, while ecological concepts were developing, scientific attention was driven primarily by physical models of nature, resources, and human utilization; and information systems were constructed in support of a fully mechanical view of nature. Whatever changes have taken place in ecological components and their functions occurred while we were looking primarily at physical and human components of the system.

There have been two major technology-driven exceptions to mechanistic (reductionistic) thinking in recent science. One was NASA's "Earth Systems Science" as a paradigm for global observations from space. It emerged from the minds of forward-thinking physical scientists (Earth System Sciences Committee, 1988) and retained a strong physical character as a way to justify technology in the context of rising global ecological concerns. Nevertheless it opened the door to systems thinking. The other, again made marketable because of its technological basis, was the growth of information science into the field of artificial life (Langton, 1995). It also retained a distinctly physical character rooted in computational complexity, but its followers had the courage to ask questions about the nature of life, something even life scientists were avoiding. Nevertheless there remains a strong tendency in both cases, reinforced by funding as well as scientific traditions, to apply old reductionisms. The result is still an excess of mechanistic thinking and continued marginalization of genuinely semantic, contextual, and system-specific elements. These efforts were significant, however, and in the direction of rising needs. They allowed us as a society to begin asking about the basis on which living system science may be established. But we have not yet arrived at an awareness that would value ecology as a science in its own right, or guide the development of more appropriate measuring and analytical tools. Today, ecosystem management needs are running far ahead of our theoretical, methodological, and technological capacity.

Ecosystems are fundamentally self-organizing, “resetting” themselves to new conditions in ways that are hard to anticipate. They will always be capable of surprising behavior, which is their most fundamental aspect. James Kay suggests that it is actually our interactions with ecosystems that are subject to management, not ecosystems themselves (Kay, 1994). For example, we manage our interactions with the economy through the specific effects of fiscal policy, taxation and subsidy, national budgets, and other economic influences, while monitoring its health and integrity according to key indicators. Similarly, we manage ecosystems through the specific effects of human development, industrial emissions, enhancement and extraction of ecological goods and services, impacts on biodiversity including species replacements and genetic alterations, pollution and water use, disease vectors, and human health, motives, and values. Also analogously with economics, we should monitor the health and integrity of ecosystems at all scales through appropriate indicators and early warning systems. In times of ecological crisis, as in analogy with the military security sector, we manage threats, not security or sustainability.

The new ecosystem perspective, or “ecosystem approach” (Kay, 1994; Kay et al., 1999), is a major departure from the usual way of separating nature into component parts, each part studied by a different discipline. In that view, biota are generally treated as separate entities from the environment, which is imagined as a larger physical system context in which organisms reside. The study of the biological “component” of nature, of itself, is biology. Ecosystems, on the other hand, are defined as including the environment. All of ecology, then, is about the relationship between organisms and the environment, but also about whole ecosystems that have their own properties. Ecology thus involves biology plus material and energy flows, and concepts of system organization. Recent trends (particularly in landscape ecology) are to include human ecology as part of general ecology, even in the study of otherwise natural systems. It is thus the bridge between biological, physical, and social systems that is capable of representing their mutual relationships. It also deals with various scales from local to global. James Kay states that *"The ecosystem approach is both analytic and synthetic. It involves analysis of living systems by disciplinary science. But understanding comes from synthesizing together the different perspectives gained from disciplinary science"* (Kay, 1994).

Concepts of complexity and general systems thinking now dominate this perspective. Living systems are complex systems, which are very different from the simple systems of Newtonian physics (Rosen, 1991a). That difference is best understood in terms of information as an intrinsic property of living systems, making them complex; and as a tool for ecosystem management allowing it to reflect natural complexity. In both cases, thinking in terms of the relationship between information and natural states is useful for understanding complexity. Uncertainty arises from such relationships; on the one hand resulting in unpredictable ecosystem behavior, and on the other hand complicating our modeling of that behavior. For example, ecosystem history, or "memory" can dominate ecosystem processes and affect current behavior (Peterson, 2002). Accordingly, our knowledge about ecosystems must include system-specific contexts and their history to be useful.

At least four major developments in general systems thinking appear to be reinforcing each other to produce a complex systems perspective on nature. The earliest on the scene was certainly economic theory, which arose with the development of human society, but became a truly global science only recently. The next in line was the development of ecology and the concept of the ecosystem, which originated with Arthur Tansley in 1935 but did not really start to advance until Eugene and Howard Odum laid out its main tenants in the mid 1950's (Odum and Odum, 1955). Related to this was the introduction of General System Theory (GST) (Von Bertalanfy, 1968). Subsequent development of GST, which saw the addition of complex systems theory and cybernetics, may now be helping ecology to sort out its troubled theoretical foundations. The other more recent developments in systems thought were driven by technology. One of these was information science, which developed inherently as a systems endeavor, sharing many analogies with aspects of living systems and now producing a global system of its own (the Internet).

Eco-Accounting: An Assessment of the Millennium Assessment

The Millennium Assessment, attempting to be state-of-the-art, adopted the framework of "Ecological Economics" (Costanza et al., 1997), which is analogous to economic accounting, complete with quantitative indicators, balance sheets and scorecards. The idea was that a precise, multi-resource, multi-sector analysis would allow problems to be identified and corrective measures to be recommended. Ecological Economics discusses and evaluates ecosystem "goods" and "services" in measurable and accountable terms. Ecosystem services are defined by the MA as *"the* *conditions and processes supported by biodiversity through which ecosystems sustain and fulfill human life."* The basic kinds of ecosystem services are:

(1) Provision of Goods ("e.g., food, water, fiber, fuel, other biological products"),

(2) Support of Functions ("e.g., biodiversity, pollination, waste treatment"), and

(3) Ground of Values ("e.g. cultural, aesthetic, and social").

Values, however, appear with more difficulty in the accounting. The hope is, perhaps, that where moral imperatives have failed in the past, showing the economic bottom line through a more full accounting of "natural capital" will allow enlightened self interest to succeed. According to the MA, "The principle benefit of such an integrated assessment is that it provides a framework for examining the inter-linkages and trade-offs among various goods and services. By looking at the production and condition of the entire array of services, trade-offs among various services become apparent."

The Millennium assessment drew on the results of multiple "integrated assessments" that attempted to be multi-sectoral. This was a change from past single-sector assessments of, for example, forest production or single species "stock" assessments. The idea was to identify the "tradeoffs" between benefits and detriments within different sectors of society with different sets of values, as depicted in **Figure I-2** (from the MA report). Benefits in one category may then be weighed against detriments in another to achieve the optimal balance for both sustainability and provision of desired goods and services. The balancing of these tradeoffs in the past has been treated politically rather than scientifically. By quantifying benefits and detriments and defining sustainability in terms of that balance, a framework may be developed for providing more rigorous information for management and policy. According to the MA: "*The principle benefit of an integrated assessment is that it provides a framework for examining the interlinkages and trade-offs among various goods and services…By looking at the production and condition of the entire array of services, trade-offs among various services become apparent.*"

Figure I-2: MA Tradeoff Spreadsheet

A problem exists, however, with the very concept of balancing or "optimizing" tradeoffs for maximum sustainable extraction of goods for human consumption. As suggested by the arrows in Figure I-2, this concept embodies two questionable assumptions. First, that the benefits and detriments of alternative scenarios is quantitative (rather than qualitative); and second that they can be related to each other as proportionally scaled measures, some decreasing predictably when others increase. These essentially linear assumptions can run counter to what is known about complex system behavior. Complex systems may at times behave in linear, proportionate ways, but at other times may behave in non-linear, disproportionate ways, exhibiting novel behavior and surprise, even "flipping" entirely to different organizational regimes with corresponding changes in environment and species. The problem in ecological accounting can be seen as stemming from its structural approach to relating measures of multi-sector, multi-resource performance whereas the trends are not structurally related but functionally and contextually related. We do not have a way of dealing with that kind of system connectivity. The spreadsheet, or "scorecard" is a structural device that implies direct linear (proportional) correlations that we know do not characterize the natural behavior of these systems.

There are additional inconsistencies in the MA. First, it speaks primarily to governments while arguing for more local control as the ultimate remedy. It states that *"measures to conserve natural resources are more likely to succeed if local communities are given ownership of them, share in the benefits, and are involved in decisions."* But such a recommendation to share power is a very difficult result to achieve. It would require very convincing socio-ecological information that does more than present data; it would have to compel a change at the heart of our personal and societal relationship to nature. Indeed, the MA recommended just such an ethical change in attitudes and beliefs, aside from the changes needed in science and informatics. However, this recommendation seems already consigned to history. The inability of "Deep Ecology" (Sessions, 1995) to accomplish this decades ago is presumably one of the factors steering modern assessments toward the language of ecological economics. To a certain extent, the MA said we cannot really afford to abandon deep ethical perspectives, and yet it does not offer a way to preserve them.

Despite its recommendations to balance tradeoffs analytically, the MA has not left a legacy different from other assessments regarding the kinds of ongoing monitoring and information systems that followed similar international programs in the physical sciences. In expressing the need to change the way society values ecosystems and thus sets priorities, the MA echoed similar pleas of past assessments, even though it recognized that these had not resulted in the kind of change called for. Like so many previous assessments, the MA's recommended changes are unlikely to happen since it presented no plan that would effect change in hearts and minds.

These shortcomings do not diminish the importance of this first-ever global assessment of the condition of our ecosystems, but they raise questions about its effectiveness to improve our understanding of ecosystems and their value. Without a central theory and method to address natural and human complexities, how well these assessments will serve to balance the alternatives meaningfully remains an open question.

There should be at least three parts to an assessment: (1) conditions and trends, (2) their meaning in the natural context, (3) their meaning in the human context. Furthermore, we need a better theoretical foundation for addressing the second two, and an approach to ecological informatics that truly integrates information from both a factual and meaningful perspective. So far, we have the theory and methods only for quantifying trends, not for analyzing functions or characterizing behavior in various contexts and within various scenarios, except on a highly instrumental and ad hoc basis.

Missing in Action: Ecological Functions

A stated goal of the Millennium Assessment was "...to increase the amount, quality, and credibility of policy-relevant scientific research findings." (Millennium Ecosystem Assessment, 2002) However, the MA was conducted as an expert panel synthesis of existing information, somewhat like the Intergovernmental Panel on Climate Change (IPCC), except that with the MA the most critical information did not exist and could not be produced. With only information about conditions and trends, and not about the ecosystem functions that produce these behaviors, it is impossible to make effective policy statements or recommendations. We can only manage the cause of trends, not the trends themselves. In contrast, the IPCC was able to make more enduring statements about global warming on the strength of extensive modeling.

Many believe that currently available information is inadequate to answer the important questions posed about ecosystems because they are much more complex than physical systems. Policy must anticipate, and to do so it must have anticipatory information about causes, processes, consequences, and meanings so that alternative solutions can be considered. Credible scenarios must be built on a solid foundation of fact and integrative theory, and presently we lack both.

As a result, ecosystem assessments (MA, PAGE, GEO-3, and IPCC) were highly redundant, citing the same sources and each other, sometimes adopting almost identical wording. New, rigorous and complete information—empirically and theoretically complete—should be introduced so that statements can be supported in non-arbitrary ways. The needed foundation should be rooted in sound science, and if new science is required, it will need to be rigorous to be accepted. Some national assessments are legally mandated (e.g.,, the Magnuson-Stevens Fisheries Act, the Endangered Species Act, and the National Environmental Policy Act). Assessments related to such mandates must often survive legal challenges in court. For that, both the assessment and the interpretation for policy must be based on strong empirical evidence within a framework of solid theory. Only that combination can result in believable forecasts and recommendations for action. In addition, we need to begin building an empirical record of assessments and related case studies of alternative management practices. The goals of "adaptive management" (Holling, 1978) should now be extended regionally and globally. This too requires new informatics.

Setting aside for the moment what such information should contain, the cry for more and better information has been apparent in each assessment and strategic plan for ecosystem management. At the beginning of the MA, its Secretariat stated:

> *"…while policymakers have ready access to information on the condition of their nation's economy, educational programs, or health care system, comparable information on the condition of ecosystems is unavailable despite the important role that they play. In fact, no nation or global institution has ever undertaken a comprehensive assessment of how well ecosystems are doing in meeting human needs" (Millennium Ecosystem Assessment, 2002).*

Similarly, in its report *"Ecological Indicators for the Nation,"* the US National Academy of Sciences stated that:

> *"Indicators are needed to inform us about ecological status and trends at all spatial and temporal scales, and at a variety of levels of specificity, ranging from the status of local populations to the functioning of large ecosystems" (National Academy of Science Commission on Geosciences, 2000).*

The Office of Science and Technology Policy (OSTP), Committee on Environment and Natural Resources (CENR) began an interagency program in "*ecological forecasting*," stating that "*to sustain the delivery of [ecological] goods and services, we need to anticipate how ecosystems will respond to natural and human stresses*". (CENR Sub-Committee on Ecological Systems, 2001)

These needs have been echoed within multiple US Agency programs. NASA's "Earth Science Enterprise," their successor to "Earth Systems Science," added a global ecosystems component (NASA, 2007). NSF, in partnership with these agencies, launched a research program for "*Biodiversity and Ecological Informatics*" (BDEI) (Maier et al., 2001). BDEI explicitly recognizes (as have the recent assessments) that ecosystems support biodiversity and that their proper functioning is necessary to support many of the goods and services that we depend on from nature. The US National Oceanic and Atmospheric Administration (NOAA) recognized the need for "*science-based management within its National Marine Fisheries Service (NMFS)*,"(Schmitten, 1998) interpreting this as "*ecosystems-based science and management*." (National Marine Fisheries Service, 1999) In a speech to the Center for Oceans Law & Policy, the NOAA Administrator listed "*Ecosystem Forecasting and Management*" as one of NOAA's top seven cross-cutting strategic priorities (Lautenbacher, 2002). NOAA has many programs potentially affected by a shift to ecosystem-based management in the NMFS, and a series of regional assessments concerning climate change/variability impacts on social, ecological, and economic sectors (NOAA Office of Global Programs, 2007). The US Geological Survey (USGS), responsible for building biological informatics for the nation, has developed a *National Biological Information Infrastructure* (NBII) to collect and organize extensive information about biological and ecological resources in the US and its territories (NBII, 2007; PCAST, 2001). They similarly recognized the high priority of "*understanding ecological functions and assessing predicted change at varying temporal and spatial scales*." (USGS, 2007)

However, none of these efforts have been able to incorporate a robust functional ecological concept into ecological informatics itself. Generally, it is recognized that we must understand function to interpret data, but we are still locked into the mindset that these two activities can be separated, one into a database and the other into general laws on which models are constructed, and that they can subsequently be managed by different sectors of the scientific establishment; with yet a third sector, presumably existing in a program office, meaningfully reassembling the components for understanding ecosystems and for making decisions or policy. None of these assumptions appear to be true. The natural relationship between data and models has yet to be appreciated as an inseparable whole. Meanwhile, we do not have an adequate concept of environmental and ecological informatics to support the lofty goals that are stated of ecosystem management and national or international policy. We do not yet understand what ecological informatics should consist of.

Conclusion

As the conscience of an economically driven society, ecology has been forced to take a back seat, even within global science programs. Its incomplete view of living nature, as described here, further marginalizes its impact. The field is often referred to as "environmental science," further conflating methods appropriate for a physical analysis with those needed to study a living system—an ecosystem. The political bias, which can even deny the existence of ecosystems (Fitzsimmons, 1999) is reflected in a strongly reductionistic physical science tradition that has been an integral part of our 200 year period of industrial growth, in which an almost exclusive reliance on the mechanistic view of nature has fit well with technological development. That view is, however, antithetical to a system view and today threatens our ability to manage the living systems we are rapidly altering.

There is an obvious disparity, made clear in the Lomborg debate, in what assessments of natural capital vs. assessments of technological progress measure. Most certainly we do not know where the combined trends will lead. We are faced with our own domination of a deeply complex and unpredictable system that we previously considered infinite in its capacity to meet human needs. Ecosystem management must now involve the complexities of human enterprise and management approaches, both having consequences that need to be assessed in concert with the natural complexities of ecosystems, which we do not yet understand. Even for technology to save us, we must still know how to manage human activity and its complex relationship to ecosystems.

Besides its practical appeal to bottom-line ecological economics, the MA also made a strong claim that only a change in human attitudes toward nature can make a lasting difference. It called for changes in national and multi-national policies, better application of sustainable practices, and technological improvements. It emphasized that, to set the proper goals, we require new values and multi-disciplinary integration.

It did not, however, provide a means to attain the deep ethical qualities mentioned. Implicitly the MA's recommendations calls for new scientific underpinnings capable of changing science, management, policy, political will, and societal values. That is a tall order, but it must now be addressed.

To the extent that these recommendations call for new information, we should distinguish between more of the same and more of something new. It seems reasonable, as in **Figure I-3**, to ask when we have "too little" or "too much" information (Michael H. Glantz, personal communication, 2002), suggesting a tradeoff between ignorance and wasted effort and money. The vertical bar in the diagram represents a threshold dividing information into two different types. To the left of the bar, information is syntactic and appropriate only for describing "simple" (i.e., mechanical) systems for which a general semantics can be applied in the form of physical law. To the right is a new kind of information based on the contextual inseparability of syntax and semantics (which, for the ecologist, translate into structure and function). The right side thus represents a different kind of information that is applicable to complex living and social systems. We can imagine that, as of today, our general informatics has reached this threshold but has not gone beyond it. Arguments for "more" information are thus quite valid, but critics also have a valid

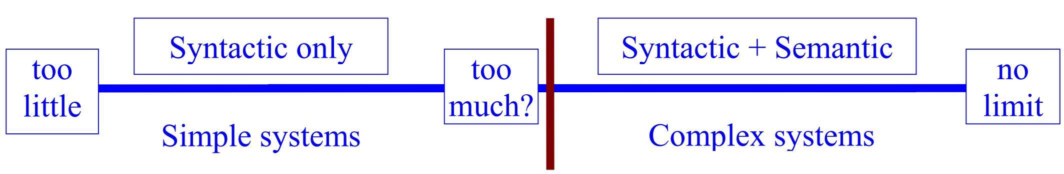

Figure I-3: Continuum of 'Useful Information' point because more of the same will not do; it must include a different kind of information if it is to make a difference.

The challenge is thus to redesign information so that it can in fact communicate meanings derived from natural context (which includes humans), such that socially constructed meanings have an anchor in both human and natural history; that is, not simply political or personal whims that can be arbitrarily substituted for a knowledge of how nature really works—knowledge of the natural functions that are missing from our information base. The trend where political or other belief systems dictate science and thought may be attributed to the practice of divorcing fact from meaning, a phenomenon that is carried over from our history of advancing physical science by generalizing its laws. That practice ignores system-dependencies and context and overlooks the local relationships that determine a system's function. In living systems the most important meanings are established by contextual (non-general) behaviors; hence it is essential in any field that deals with complex, system-dependent phenomena, to capture those relations in the informatics alongside data about conditions and events. It is true in every case, that when the functions of a given system are unknown, the data about it are literally meaningless.

For the reasons discussed, current environmental and ecosystem assessments lack both the empirical platform and the theoretical underpinning needed to state defensible conclusions. And yet relatively little attention and funding are given to studying living systems. I have argued that this shortcoming has two causes. First, the historical and still traditional reductionistic bias in science sets the expectation that we should have general measures and general laws, whereas living systems have unique system dependencies that should be captured more holistically, in context. Second, the physical bias in informatics, which exists for the same reason, renders information incomplete by divorcing it from contextual function. This makes whatever information we have about ecosystems and their biological properties essentially meaningless with regard to management and policy. The predictable result of continuing this trend will be more spin-driven science, and its ultimate disenfranchisement from society.

When contextual meanings are lost they cannot be accurately recovered later through human analogy, although there are enough similarities (because humans came from nature) to make one's preconceived interpretations seem reasonable, or even obvious within a given frame of mind. The problem is similar to quoting a phrase out of context and then giving it another meaning. The result, as can be seen today, is extreme polarity of opinions and very little genuine communication. When this is done with regard to nature, even the original context—nature itself—loses its credibility, allowing society to further devalue it.

The alternative is to provide more complete information that is harder to spin. The terms of reference for that must exist in concepts that are prior to empirical measures; for, as we will see in Chapter Two, it is the ontology of systems (their origin) that is missing from a mechanical analysis. In contrast, it is the immediate presence and effect of ontology in behavior that characterizes living systems. This understanding should force ecology to begin a thorough re-examination of causality itself, free of the prior assumptions that were made to describe mechanisms.

This approach would address the problem of the MA and similar assessments discussed above, where they generally call for deep ethics on the one hand but on the other hand employ only mechanistic theory and methods applied to ecology through economic theory. This leaves social and political construction without the deep information called for to inform values. The result is necessarily superficial and what passes for "deep" ethics becomes more a deep application of instrumental values. A stronger theoretical basis for discovering or deriving ethics requires, first, that we define suitable terms of reference for articulating values and meanings, which can exist only as epiphenomena in the mechanistic view.

These arguments support the need for a deep meta-theoretical consideration of information relations that exist not just in science, but also *in* nature; a conclusion also reached, for example, by Gregory Bateson (Bateson, 1979; Kineman and Kumar, 2007). That approach is capable of supplying the necessary scientific ontology (explanation of origins) because information relations exist outside the dynamics of systems being related, as part of their larger context (Rosen, 1991b). In that entirely legitimate way, origins of systems can be considered and stronger concepts of function and meaning can be defined as contextual relations. From that foundation value and ethics can also be explored as, perhaps, properties of nature or as derived from human nature, or from our interactions with nature. Regarding ecological assessments, information can thus be seen as an ecosystem service; to human society (from natural wisdom to biotechnology), and back to nature itself, to supply self-sustaining feedbacks within an organism or ecosystem. We must move to this new kind of analysis to represent the effects of ontological complexity.

Chapter One Supplement: What the Assessments Say

Acronyms

1. Global Environmental Outlook -3 (GEO-3) (UNEP, 2002)
2. PAGE (WRI, 2000)
3. IPCC (Gitay, 2001) (Solomon et al., 2007)
4. Millennium Ecosystem Assessment (MA) (Millennium Ecosystem Assessment Board, 2005)

Ecosystems and their Goods and Services:

- GEO-3: "*There has been immense change in both human and environmental conditions over the past 30 years…In many areas, the state of the environment is much more fragile and degraded than it was in 1972.*"
- PAGE: "*...nearly every measure we use to assess the health of ecosystems tells us we are drawing on them more than ever and degrading them, in some cases at an accelerating pace.*" "*In all five ecosystem types PAGE analyzed, ecosystem capacity is decreasing over a range of goods and services, not just one or two.*" *Human demand for ecosystem goods and services is growing dramatically…We have made, and are making, changes to ecosystems of unprecedented magnitude.*"
- IPCC: "*Most modeling studies continue to show the potential for significant disruption of ecosystems under climate change.*"
- MA: *"The structure of the world's ecosystems changed more rapidly in the second half of the twentieth century than at any time in recorded human history, and virtually all of Earth's ecosystems have now been significantly transformed through human actions."… "The degradation of ecosystem services could grow significantly worse during the first half of this century and is a barrier to achieving the Millennium Development Goals.*"

Water:

- PAGE: "*One third of the world's population is now subject to water scarcity. That population will double over the next 30 years.*"
- GEO-3: "*About one-third of the world's population lives in countries suffering from moderate to-high water stress—where water consumption is more than 10 percent of renewable freshwater resources.*"
- IPCC: "*Climate change challenges existing water resources management practices by adding additional uncertainty"….* "*Degradation of soil and water resources is one of the major future challenges for global agriculture.*"
- MA: *"The amount of water impounded behind dams quadrupled since 1960, and three to six times as much water is held in reservoirs as in natural rivers. Water withdrawals from rivers and lakes doubled since 1960; most water use (70% worldwide) is for agriculture." …"Since 1960, flows of reactive (biologically available) nitrogen in terrestrial ecosystems have doubled, and flows of phosphorus have tripled, water use doubled."*

Population and agriculture:

- GEO-3: "*The trend during the decade 1895-95 showed population growth racing ahead of food production in many parts of the world.*"
- PAGE: "*Food production must increase to meet the needs of an additional 3 billion people in the next 30 years.*" IPCC: "*... the beneficial effects of elevated CO2 on the yield of [tested] crops are well established...[however] grain and forage quality declines with CO2 enrichment and higher temperatures.*"
- MA: *"More land was converted to cropland in the 30 years after1950 than in the 150 years between 1700 and 1850. Cultivated systems … now cover one quarter of Earth's terrestrial surface." "Between 1960 and 2000, the demand for ecosystem services grew significantly as world population doubled to 6 billion people and the global economy increased more than six-fold. To meet this demand, food production increased by roughly two-and-a half times, water use doubled, wood harvests for pulp and paper production tripled, installed hydropower capacity doubled, and timber production increased by more than half."*

Deforestation:

- GEO-3: "*Deforestation over the past 30 years has been the continuation of a process with a long history. The net loss in global forest area during the 1990's was about 94 million ha (equivalent to 2.4 percent of the total forests). Deforestation of tropical forests is almost 1 percent annually.*"
- PAGE: "*Global forest cover has been reduced by at least 20 percent since pre-agricultural times, possibly by 50 percent.*"
- IPCC: "*Loss in forest cover appears to have slowed in recent years…however fragmentation, non-sustainable logging of mature forests, degradation, and development of infrastructure—all leading to losses in biomass—have occurred over significant areas in developing and developed countries.*"
- MA: *"From 1990 to 2000, the global area of temperate forest increased by almost 3 million hectares per year, while deforestation in the tropics occurred at an average rate exceeding 12 million hectares per year over the past two decades (C.SDM)."*

Biodiversity

- PAGE: "*Biodiversity underlies all other goods and services and provides "goods" in its own right.*"
- GEO-3: "*Biodiversity will continue under threat if there is no strenuous policy action to curb human activity.*" "*Global biodiversity is being lost at a rate many times higher than that of natural extinction due to land conversion, climate change, pollution, unsustainable harvesting of natural resources, and the introduction of exotic species.*"
- PAGE: "*An estimated 10-15% of the world's species will be committed to extinction over the next 30 years.*"
- IPCC: "*25% of the world's mammals and 12% of birds are at significant risk of global extinction…the extinction rate of invertebrates in tropical forests alone has been estimated at 27,000 per year, largely because of habitat conversion.*"

- MA: Ecosystem change *"…has resulted in a substantial and largely irreversible loss in the diversity of life on Earth."*

Climate Change:

- GEO-3: "*Climate change represents an important additional stress on those ecosystems already affected by increasing resource demands, unsustainable management practices and pollution.*"
- IPCC: "*Ecosystems are subject to many pressures…; their extent and pattern of distribution is changing, and landscapes are becoming more fragmented. Climate change constitutes an additional pressure that could change or endanger ecosystems and the many goods and services they provide.*"
- MA: *"recent changes in climate, especially warmer regional temperatures, have already had significant impacts on biodiversity and ecosystems, including causing changes in species distributions, population sizes, the timing of reproduction or migration events, and an increase in the frequency of pest and disease outbreaks".*

Chapter Two:

Modeling Relations in Nature and Ecological informatics

A Practical Application of Rosennean Complexity

Abstract

The purpose of ecological informatics is to communicate critical information about organisms and ecosystems to humanity. To accomplish this, it must reflect the complexity of natural systems. Present information systems are designed around mechanistic concepts that do not allow them to capture natural complexity. Robert Rosen's relational theory offers a way of representing complexity in terms of information entailments that are part of an ontologically implicit "modeling relation" in nature. That relation has corresponding epistemological components that can be captured empirically for science and informatics. The empirical components of the modeling relation are structure (associated with model encoding) and function (associated with model decoding). Relational complexity thus provides a much-needed theoretical underpinning for these concepts that ecology has found indispensable, including their natural relationships which can provide a new foundation for ecological informatics. Structural information pertains to the material presence of a system, which can be measured and represented by data. Functional information specifies potential change which can be inferred from experiment and represented as models or descriptions of state transformations. Contextual dependency (of structure or function) implies meaning (for that context). Biological and ecological functions can be distinguished from physical functions in that they involve internalized or system-dependent laws rather than general ones. Such

internalization of cause leads to uncertainty in process. Consequently functions must be recorded in the original context where they are discovered, because they cannot be recovered later from general principles. Complexity can be represented epistemologically by relating structure and function to each other in two different ways. The first is the direct expression of a function of a given system in observable behavior and its effects on the same or another system. This must be coupled with system control, which can be expressed as the suitability for that functional system in context, in terms of a generalized niche model. The other type of relation is an indirect relation of many possible functions that a structure could express, or many possible structures to could actualize a function; allowing structural and functional replacement or overlap. This second relation draws the complex ontology of a system into the empirical world in terms of multiple potentials subject to natural forms of selection and optimality, acting as system attractors. Implementing these components and their theoretical relations in an informatics system will provide more complete ecological information than is possible from a strictly mechanistic point of view. The approach will enable many new possibilities for supporting science and decision making.

Introduction

The goal of ecosystem informatics is to support science and to inform society so that important choices can be made about ecological resources (Cushing and Wilson, 2004). This requires that informatics provide effective communication of not only what exists in living nature, but also of what it is prone to do under different circumstances, so that we can understand and manage it. This is not just a practical problem for presently there is no adequate theoretical definition of life (Cleland and Chyba, 2007). Cleland and Chyba wrote: *"But if life is a natural kind, we need a theoretical framework for biology that will support a deeper understanding of life than can be provided by the features that we currently use to recognize it on Earth."* (Cleland and Chyba, 2002)

Present ecological informatics focuses on physical concepts and measures of environment and organic systems (objectified via classification), reflecting a mechanistic bias in the history of environmental science and informatics (Chapter One; Kineman, 2003b). Physical science has traditionally excluded the study of the origin of material systems (ontology) because the mechanistic view necessarily represents as a singularity before time and existence. Similarly, ecology is defined as a study of presently existing systems, treating it as a separate science from evolution. The poor theoretical integration of ecology and evolution allows the mechanical view to dominate both fields, where general physical causes can be thought to determine both the origin and behavior of biological categories in a one-way causality. That theoretical restriction excludes consideration of any strictly biological causes, whereas opening science to that possibility seems logically necessary not only to unify these theories, but also to deal with ecological complexity (Kineman, 2003a; Kineman, 2007). Theoretical inconsistency and fragmentation of science along these lines has been shown to result from the assumptions and limits of the mechanistic view itself (Rosen, 1985b; Rosen, 1991a). As a result, mechanism cannot provide an adequate foundation for understanding the complex nature and behavior of ecological systems, which must involve a logical origin for novel behavior. If we are concerned about the appropriate design of ecological informatics such that it can capture complexity, we must look to a different mode of analysis and representation of nature.

Robert Rosen developed, over the course of his lifetime, a meta-theory of life based on Nicholas Rashevsky's "relational biology" (Rosen, 1978; Rosen, 1985a; Rosen, 1991b; Rosen, 1999).[5] His research demonstrated that the mechanistic concept of nature is too theoretically and mathematically "impoverished" to describe living systems. Mechanism turns out to be a special case of Rosen's general theory, which I shall call *relational complexity*. Advances in Systems Biology (Konopka, 2007), and information science (Capurro and Hjoerland, 2003) bring us closer to the concept of *"complete information"*[6] (Fudenberg and Tirole, 1993), where , as in Rosen's *"relational biology,"* the explanation of complex nature can be made in terms of information relations (Bateson, 1979; Ulanowicz, 2001; Kineman and Kumar, 2006; Kineman, Banathy, and Rosen, 2007).

Rosen's relational perspective was originally introduced as a description of natural science, that is, the relationship between nature and scientific models (Dress, 1999). Here I explore its implications of Rosen's view of how nature may be internally related through information; that is, defining an information relational ontology within natural systems. The most general form of that ontology is free of, and logically prior to, the imposition of mechanistic constraints, thus allowing the theory to consider more general phenomena. The approach focuses on the relationship

[5] Rosen produced a lifetime of publications on relational theory to answer his central question: What is life? (See: http://www.panmere.com/rosen/biblio.htm).
[6] See Wikipedia, http://en.wikipedia.org/wiki/Complete_information, August 2007

between the measurable aspects of a system, and system-specific natural functions that represent potentials for system behavior and development. While the broader implications of this view of nature will not be explored in depth here, it is essential to approach it as a general theory. As with any new scientific view, only after considerable application will the practical extent of its assumptions be known.

Dealing with the Dual

There are many precedents for dualism in science and no less in ecology. For example, landscape ecology is traditionally framed in terms of "pattern and process" (Turner, Gardner, and O'Neill, 2001: pg. 404), which is a mechanistic duality. Similarly, the terms '*structure* and *function,'* on which the epistemology developed here will be based, are frequently used together to imply some kind of complementary relationship, but without clear definitions. Most often ecologists think of them, inappropriately as we will see, as complements of a mechanism while also implying vague ideas of potential and purpose. As a result of this poor theoretical understanding, there is considerable confusion in ecology about what these terms refer to and how they are related (Hochstrasser and Yao, 2003). Landscape ecology, because it tries to combine human and natural systems, has had to confront many of these inconsistencies. Risser questioned these and other definitions, writing *"we must think bravely and with contemplative recklessness...advancing Landscape Ecology will require thinking in innovative ways that are not restricted by the extant concepts and methods of related disciplines"* (Risser, 1987). Much more work is needed, as Allen and Starr emphasized while boldly introducing *"hierarchy theory,"* of which they wrote: *"What is new here is a formal acceptance of complexity in its own right.*

It is more than something encountered in the systems at hand--complexity is something that needs more than an ad hoc treatment" (Allen and Starr, 1982). A first step toward true complexity for Landscape Ecology, in accordance with both Allen and Rosen, would be to define at least one side of the relation in a non-material way. For most scientists, *process* is equated with material dynamics; however, material *patterns* exist in both space and time and thus include both state and dynamics. While such analysis of pattern is essential in observational studies, it becomes clear, for example in relating different scales, that something more is needed to address or explain system complexity (Wessman and Bateson, 2006). '*Pattern and potential'* might define a more complex dichotomy (see Chapter Three), as do *structure and function* in Rosen's view. The analogous duality in language, is *'syntax and semantics,'* or (reversing the order) *'subject and object,'* and in both physics and epistemology we have *'observer and observed.'* Throughout human thinking, a complementarity principle has been involved in our concept of nature, between related properties that combine with but cannot be reduced to each other. Von Neumann referred to the duality in science as the *"epistemic cut,"* or difference between knowledge and reality (Pattee, 1995). Alfred Korzybski famously stated it as the difference between *"map and territory"* (Korzybski, 1933). These are all related ideas, which Rosen captured under the most general heading of *"mind-body"* dualism (Rosen, 1993) and expressed in categorical language as a *"modeling relation,"* which I will discuss in some detail later. Rosen's modeling relation is unique among these dichotomies in that, when applied naturalistically, it is explicitly self-entailed, like life itself. It specifies a relation between a complex natural system and any system that describes it, very much like von Neumann's epistemic cut, except that Rosen attributed it to nature itself and presented it not as a duality but as a complementarity, preserving its wholeness properties in a new kind of relational analysis. This view of nature implies an infinite holarchy of self-similar relations, (Kineman and Kineman, 1999) and in this way it bridges the traditional duality and becomes non-dual in the limit. It is thus an ideal philosophical instrument for representing whole, complex realities such as living systems and a significant portion of this paper is devoted to describing it and its implications.

Rosen's relational theory interpreted in terms of well-defined structure-function relationships provides a fresh look at ecological theory. Ecology itself has historically suffered from lack of a central theory (Simberloff, 1981), and while ecologists continue to make strong calls for "new thinking" (Risser, 1987; Allen and Starr, 1982; Bateson, 1972; Huston, 2002; Scott et al., 2002), most approaches in Systems Biology are still dominated by computational theory (Herwig et al., 2004). A recent critique of systems biology stated:

> *"The reductionist approach remains dominant, however, and systems biology is often seen as no more than integration of diverse data into models of systems. This way of thinking needs to be changed if systems biology is to lead to an understanding of life and to provide the benefits that are expected from it"* (Cornish-Bowden and Cárdenas, 2005).

Questioning Mechanism

Rosen wrote extensively about the limits of science, which are much broader than the limits of mechanism (Rosen, 2003a). He claimed that relational analysis is a more general scientific approach than mechanistic analysis because mechanism assumes prior universal constraints (*the* "natural laws"), and therefore does not discuss their origin, whereas Rosen's relational perspective considers constraints that are system-defined. The relational view thus allows both local and general system constraints (laws) to be considered. It is natural to many ecologists to think in terms of system-dependent phenomena, but it can be considered non-rigorous in the traditional logic of mechanical systems.

The problem is that a mechanical analysis deals with state-reference, which is fundamentally a concept of separated, discrete and non-related entities. Accordingly it cannot represent the common source of states; it must represent all origins as a prior singularity, i.e., before the analysis, before the beginning of space and time which are the terms on which state dynamics are defined. Similarly, if we assume that the behavior of states has a general causality, that also constitutes an origin: an origin of behavior. The laws of behavior, therefore, *must* be pushed outside the world system that manifests such laws. Therefore, no new laws of behavior are allowed to originate since the 'beginning' or after the origin of natural law, and all that happens must be described as a re-configuration of prior systems according to pre-existing laws. Consequently, no fundamentally new kind of causal system can exist at all in that view. This agreement among scientists to explain natural events in this way was effective for describing physical systems but not living ones. What Rosen found to be most profound about biology was that organisms do indeed represent a different kind of causal system, defined by locally entrained and internalized causal relations that isolate them from the general causal system, and hence from the possibility of full explanation in terms of general laws. In that sense, they exhibit partly 'original' behaviors.

There have been clear historical precedents, from the work of Whitehead, Elsasser, Chaisson, and others (Ulanowicz, 2007), for the idea that biology is different from traditional physics in that it involves a new kind of causality associated with the definition and influence of categories, and hence the entailment of semantics. Rosen focused on Goedel's proof of the incompleteness of number theory as final evidence that semantics are actually involved generally, implying that mechanisms must be approximate and temporary cases of the complex. Goedel's proof destroyed the goal of "finitary" mathematics, which was to show once and for all that a system of symbolic logic (number theory) can itself be complete and thus provide complete descriptions of nature. The destruction of this idea shook up mathematics and physics, which have still not fully grappled with the idea that all analytical descriptions imply (or require) contextual semantics.

A simple example of how natural referents are essential to interpreting numbers can be seen in simple addition. It is an axiom of number theory that one 'thing' plus another 'thing' sums to two 'things.' This is based on discrete logic, i.e., the logic and semantics of discrete entities or choices. It is also clear, and implicit throughout the relational theory, that when two *systems* combine or interact there is always a third 'emergent' system produced (or implied). If we combine two ecosystems we have an ecotone. If we combine two cultures we have a hybrid culture. Living systems, being sensitive to their environment, always form such relationships. Thus, if we are to think systemically, the 'third alternative' appears naturally—it is a combination of the previous systems or ideas held as opposites, and yet in some way transcending them. We can thus say that $1 + 1 \Rightarrow 3$; that the sum or interaction of two systems produces three systems, not two. Number theory can provide combinatorics for such results (the number of systems resulting from the combination or interaction of n discrete systems is 2^n-1); however, this or any other method of counting 'emergent' systems does not commute in finitary number theory. When the combinations of a previous combination are added, there results a fundamental ambiguity as to how many new systems to include and from what perspective, since the definition of each system depends on its interactions (the same problem encountered in quantum theory, as discussed below). This result supports the view that the functions of each system interaction must be considered uniquely and recorded with respect to their original context. Furthermore, the concept of 'emergence' is clearly an artifact of the mechanistic/quantitative analysis; whereas the "third" system exists quite naturally in a relational analysis (Ulanowicz, 2007).

The mechanistic perspective was so successful during the modern era of Western science that it established itself in most of the sciences, at least as an ideal. One of its tenets, and desirable features, is that pre-determined mechanisms have predictable futures; however, it is now clear that complex systems do not conform to this ideal. After a number of cracks began to appear in this edifice, the dream of absolute determinism and causal generality was finally shattered at a fundamental level in science with the discovery of quantum behavior. Living, and certainly cognitive systems, exhibit indeterminate behavior similar to quantum *observership*, where states are co-determined by interacting systems (Wigner, 1981; Schlosshauer, 2004; Wheeler, 1981). Yet because we must accept that all theories are approximations, the question remains if the uncertainties appearing in the micro or macro world should be attributed to the epistemology (i.e., analytical *error*, about which we say no more), or to the ontology (i.e., theoretical *indeterminism* about which new theories can be proposed). The quantum discoveries legitimized scientific inquiry into the possible causes of indeterminism, thus confirming that ontology is inescapably a part of science. This was a disturbing event that transformed the philosophy of science and divided physics into two camps: quantum realists and those who are content with statistical mechanics. It also introduced the *post-modern* era (Popper, 1965; Kuhn, 1970; Lakatos, 1974), demarcated by a rejection of *logical positivism*, and beginning of a broader inquiry into the meta-theoretical assumptions on which scientific knowledge is necessarily based (Stanesby, 1985). Unfortunately this change has yet to propagate fully into the life sciences, which have long sought to emulate the traditional view of mechanism (Platt, 1964).

Rosen's relational complexity is a post-modern inquiry into new meta-theoretical roots regarding living systems. It can accordingly be distinguished from theories of deterministic and computational complexity which Rosen termed *"complication"* (Rosen, 1999: pg. 133). True complexity, in Rosen's terms, cannot be explained as a mere complication of mechanistic events and processes, because it involves more general entailments in nature than are allowed in the mechanistic view (Kineman, 2003a). Rosen's approach frames indeterminacy as a property of interaction between natural systems in which mutual change is induced but not rigidly determined. I will refer to these relations as *inductions,* which can be described in terms of information relations that constitute formative potentials, not unlike potential fields in physics except that they follow local laws instead of general ones. The idea of potentials pertains to multiple functions that operate on the structural configuration (state space). Potentials imply a kind of system attraction or selection. Hence the present reality is represented as having attractive '*potentials* for system change. These are composable and decomposable and they can be made explicit in terms of future possibilities (functions and their respective niche models).

Like their underlying modeling relation, structure and function are complementary aspects of one natural component. In no case are they to be considered to exist separately, although they can act independently in interactions; and information about each of them can be extracted as desired. The internal relations of the informatics system should therefore ensure this connectivity, as originally discovered in nature. The approach thus establishes *relationship* as the fundamental 'reality,' or meta-theoretical foundation. It does not preclude general functions (as in mechanisms) nor, in fact, functions from any contextual level, which would be similarly mixed among local biological and general physical constraints. The view is highly appropriate for ecology, where the fundamental units of concern are categorical and system-defined, and where we must be concerned with their functional properties as well as their structural organization.

The Concept of Entailment

Establishment of this relational science begins with an appropriate concept of organization that is more locally involved than the simple division between natural behavior and natural law that mechanism imposes as reductive logic. Rosen employed the general concept of *entailment* to describe complex organization. *Entailment* involves any condition in nature or logic that is necessary for another to exist or to be true. He defined entailment most generally as the answer to the question "why B?" where B is some aspect of a system. The answer "because A" indicates the conditional situation where A entails B (or B is entailed by A); which is also represented in the statement “if A, then B.” A and B may be natural or propositional conditions. Entailment can also be described in terms of a function that operates on A to obtain or imply B. With this broad definition it is possible to recognize all four of Aristotle's ‘causalities’—*material, efficient, formal, and final*—as natural entailment relations and therefore different kinds of natural explanation (Kineman, 2003a). If only material and efficient causes are considered, a strict *duality* is established between natural and formal worlds, leading directly to the mechanistic view. When formal cause is considered, it is then possible to discuss entailments between natural and formal systems—the idea that information is an operative process *in* nature. When final cause is considered it is possible to discuss goal direction; to explain, for example, B in terms of what it entails (e.g., C) rather than what entails it (i.e., A) (Rosen, 1999: pg. 95).

Rosen applied specific ideas of *causality* and *inference* as labels for, respectively, natural entailment (natural relationships) and logical entailment (formal relationships). Mechanistic causality and its corresponding mode of positivistic inference define subsets in each of these definitions respectively. Rosen analyzed the mathematical assumptions that were imposed to restrict entailment to predictable relations, which turns out to define mechanisms (Rosen, 2003a). By reverting to a less restricted definition of entailment, before the mechanistic constraints are assumed, we can speak of richer relationships that are capable of representing the complex aspects of nature that living systems characteristically bring into their behavior (Rosen, 1991b: pg. 2-6). Accordingly, complex systems, are less predictable than mechanisms, but we gain in another way; the use of analogy.

Relationship involves the correspondence of *causal* and *inferential* entailments, and in a sense establishes a third relation, which is a mutual induction of material and mimetic change between natural systems that are in relationship.[7] This key aspect is discussed below in terms of *modeling relations.* Whereas science can be viewed as an exercise in constructing correspondences between models and material nature, the organization of nature itself, in relational theory, can be viewed as involving precisely the same kind of relations.

The first two of Aristotle's causal/explanatory categories can be considered mechanistic and 'physical' in the traditional sense. It is the last two causalities that implicate additional, locally-entailed laws of living systems and relational complexity (Kineman, 2003a). The unique properties of the relationship between natural and formal systems allow relational theory to escape the traditional assumption that living systems are constructed as complicated mechanisms and are thus describable that way (Rosen, 1958a). Because the relational approach describes a natural system in terms of intrinsic information relations the approach lends itself well as a foundation for ecological informatics; that is, the information system can be designed along presumed natural lines. I will present this case in more detail, starting with a look at our present concepts of information and how they relate to our concepts of nature.

[7] Natural systems and formal systems are not fundamentally distinct. The point is that all natural systems are also models of systems they interact with, but it is most useful to analyze interaction as a modeling relation. Even human modeling requires a natural system of which the model is a part (the brain, computer, pen & paper, etc.). In this sense, every system is both natural and mimetic.

Theories of Information and Communication

Physical Concepts of Information

The traditional concept of data and information for environmental science dates back to the 1950's and was an outcome of World War II cryptography research (Corning, 2001). The concept was distinctly physical, making environmental data since then almost entirely about physical systems (Chapter One; Kineman, 2003b). Information was defined in terms of one-way transmission models, which formed the basis for a theory of communication that has survived until today. But problems arise in applying physical concepts of information to living systems. Recognizing this problem, Schrödinger associated life with the concept of organization in his famous book: *What is Life?* (Schrödinger, 1943). Reasoning from thermodynamics, he identified "order" with a measure of "neg-entropy," the opposite of entropy. The ability of life to organize was thus correlated with the availability of usable energy to fuel dissipative systems. In somewhat of a leap, Shannon took neg-entropy as a measure of information, replacing Boltzman's thermodynamic variable 'W' with the probability that any given event may occur. 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'

This, however, was only an index of information content, not a definition of what information is or where it comes from. Shannon and Weaver introduced the concept of information as *"that which reduces uncertainty"* (Shannon and Weaver, 1972). This led to the definition of information as "*that which makes a change in* *probability assignment"* (Tribus and McIrvine, 1971cited in; Ulanowicz, 1997). Thus we have the idea that information affects the definition of states, but no idea of how. Communication theory, more or less by default, assumed a mechanistic transmission metaphor, treating information as a material object. This metaphor can be seen in the Shannon-Weaver-Wiener communication model (**Figure II-1**) (Underwood, 2003). Wiener, apparently, was aware that their concept was missing semantic (i.e., meaningful and thus interpretive) aspects (Capurro and Hjoerland, 2003).

This linear concept of information transmission permeates our data and informatics thinking today. Information is treated as though it is "something," i.e., some "thing," that goes from one location to another, can be stored, and is very much like a physical object. It is clear that data can be stored as physical recordings that can be transmitted, but data represent only one aspect of information; it can describe a pattern, but not the meaning of the pattern. It is thus semantically incomplete. Thus, a set of data can communicate only if the means for interpretation (the semantics) are general or otherwise known to the reader, which of course was the whole point of cryptography; it was intentional to obscure the meaning of a message until it reached its destination, and this requires only that one adopt an information relationship in which the semantic interpretation is generally unknown. To be obscure is, of course, not the goal of ecosystem informatics if we wish it to be accessible by policy analysts and the general public, and yet it fits just this criterion, that the semantic interpretation of ecological facts is not obtainable from general laws. We should then remember that data alone, situated only within number theory and having only physical law for its functional interpretation, offers a quantitative syntax that is incomplete first in the Goedellian sense of externalizing semantic reference, and second in the Rosennean sense of not including internally defined semantics and thus ignoring complex function.

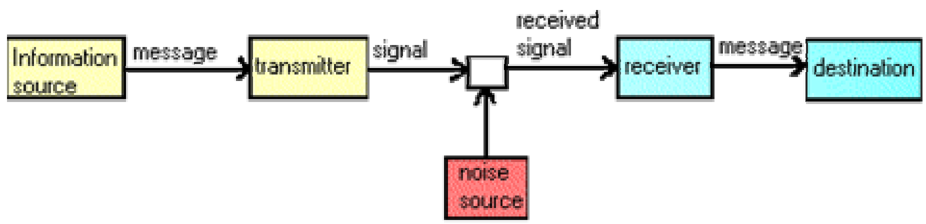

Figure II-1: Shannon-Weaver Model

The concept of state, on which data are measured, has worked reasonably well as a model for physical systems because physics does provide a well-known general interpretive context; but it has failed even in physics where that context no longer holds, e.g., .in the quantum world. The problem is thus serious for complex systems where interpretation depends on knowing the original context. Without knowledge of the original functional interpretation of a pattern, and for questions about phenomena where a general interpretation does not apply, the pattern of data is then absolutely meaningless (Kineman, 1989).

Critics of this transmission model have pointed out that information is not removed from its source when it is “sent”; hence information is not the “thing” that is actually transmitted or conducted. Context obviously has a major role in shaping how patterns are exchanged and interpreted. Whereas error is depicted as the addition of “noise,” uncertainty may also be intrinsic in information relations. Incompleteness in replicating information is part of the nature of information relations: not the result of something added but something subtracted in the encoding process by the act of abstraction (Rosen, 1994). The physical transmission model thus cannot consider complexity, nor is it designed to transmit meaning. It accomplishes its purpose by transmitting only syntax for which the semantics are either presumed to exist as general knowledge, or, in the case of cryptography, unknown to all but the sender and receiver. Furthermore, because of its decoupling with functional relations, such a model may only communicate deterministic patterns, for if they involved any indeterminism they could not later be uniquely interpreted by the pre-established decoding rules. Hence, from this concept of information we may store data measured on natural states knowing of uncertainties in those states, but we can communicate only a rigid pattern of states as if they came from a mechanism. None of the uncertainties, meanings, or multiple possibilities of a system can thus be represented as data (which the Shannon-Weaver concept of information reduces to).

Criticism of traditional information theory thus centers on the following points:

- The mechanical "conduit" and "transmission" metaphor,
- The lack of contextual influence,
- The lack of reference to meaning (functional interpretation),
- Implicit reduction to state measures and thus mechanical representation.

These mechanical properties make the traditional information transmission model and its implicit definitions inappropriate for describing communication between or within complex living systems. An informatics system that treats information as a physical unit will necessarily miss much of the natural world and suffer accordingly in communicating within human society. To capture some sense of the whole of living systems, we need a broader information concept.

The idea of thermodynamic order has been revisited for this purpose, most notably in regard to "network thermodynamics." Robert Ulanowicz, for example, defined information in thermodynamic terms as: *"Effects of that which imparts order or pattern to a system"* (Ulanowicz, 1997). In saying that information is an action imparting order or changing probabilities, he was basically agreeing with Schrödinger, but not as yet saying what that action is. Corning attempted to fill that gap with a concept of "control information" (Corning, 2001) which presumably would be *the effects of that which controls a system*, as, for example, in catalytic processes. This too, useful as it may be, begs the definition of what produces control information. A modern definition of information in "second-order" cybernetics is: *"the meaning of the representation of a fact (or of a message) for the receiver*" (Heylighen, 2003). But then we have to say what "meaning" is and how to represent it, which is not out of the question, but it does not make a good definition. The field of biosemiotics (Hoffmeyer, 1997) attempts to add the contextual and semantic elements this question implies, but according to Corning it does not yet escape the problems of traditional linear transmission theory. A hint at some internal system drive toward certain forms of order has been proposed by Ulanowicz in a principle of "ascendancy" based in part on Rosen principles (Ulanowicz, 2001; Ulanowicz and Abarca-Arenas, 1997; Ulanowicz, 1997).

While there may be considerable necessary variation in concepts of information across disciplines (Capurro and Hjoerland, 2003), I believe it is possible to define information more clearly using Rosen's relational concepts. A closer look at his modeling relation will lay the foundation for a new concept of information and informatics.

A Relational Theory of Natural Information and 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 (Personal Communication, 2005)*

Robert Rosen expressed complex entailment in terms of "*modeling relations,"* (**Figure II-2**) at the foundation of his theory of relational complexity (Rosen, 1985a: pg. 74). He first applied the idea as a description of science, showing how we copy nature in scientific models of its behavior (*encoding*), and then how we subsequently test and use

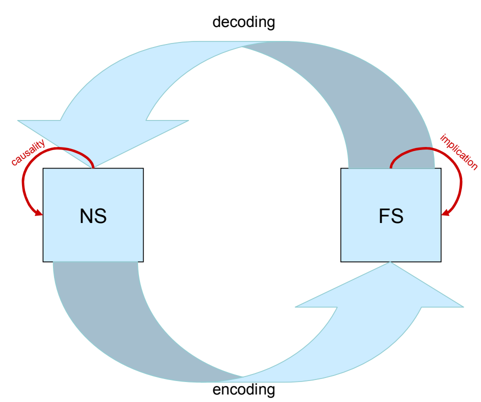

Figure II-2: The Modeling Relation
NS = "Natural System"
FS = "Formal System"

those models for prediction or management (*decoding*). The modeling relation describes these information inductions taking place between natural and formal systems. As his work progressed, it became apparent, in considering the source of complexity and its manifestation as anticipatory behavior in organismic life, that modeling relations can exist between two formal systems (Rosen, 1985a: pg. 89f), and that something entirely analogous to the modeling relation is at work in nature, between natural systems (Rosen, 1991b: pg. 62 and 122). The broader entailments discussed earlier may therefore exist in science and nature, and can be described as information relations (encoding and decoding) between two systems, where one or both systems act as a model of the other. Rosen's modeling relation presents this basic idea as a set of information relations that are the essence of *interaction* between any two systems, and whereby *natural* and *formal* properties are thus established in the ontology of nature. He concluded that the complex organization of a living organism should be thought of as containing "*internal predictive models*" that are "*functional components*"[8] acting in the same sense as a formal system of specifications that is fully entailed with the material properties of the system. Behaviors attributable to the organism are thus to be seen as acting in response to such internal models. Rosen called this kind of behavior "anticipatory"[9] because it applies a model to future events.

While similar ideas have been proposed in philosophy, Rosen was unique in developing a rigorous general theory that can be applied to all disciplines where consideration of complexity is important. The mathematical context of relational theory is category theory, which is also foundational in mathematics (Rosen, 1958a; Louie, 1985). Rosen's implicit system organization is thus foundational to science itself and suggests a revolutionary expansion of our world view as a society (Kineman and Kumar, 2007). This revolutionary implication, which demanded a very

[8] Which may not be physically identifiable, but diffuse functional/ontological aspects of the whole system.
[9] This is a reversal of the traditional view of "emergence of spontaneous novelty"(Cornish-Bowden and Cárdenas, 2005), which from the mechanistic view requires something supernatural. It is more natural to consider modeling relations as the fundamental reality, which is expressed as life by systems that internalize it, or collapsed by general constraints to state-based mechanisms.

technical presentation, has made it difficult for his work to gain wide acceptance. We will see, however, that the theory (or meta-theory) is fully consistent with mechanistic science as a special case, relational theory being the general case (Kineman, 2007; Rosen, 1991a; Rosen, 1990). Furthermore, the relational theory and its explicit concept of function remain inside natural science. Rosen wrote:

> *"… there is nothing in the relational strategy that is unphysical, in the sense of 'ideal' physics. The organization of a natural system (and in particular, of a biological organism) is at least as much a part of its material reality as the specific particles that constitute it at a given time, perhaps indeed more so. As such it can be modeled or described, in full accord with Natural Law; the resulting formalisms have at least as much right to be called images of material reality as any reductionistic model based on states and dynamical laws" (Rosen, 1991b: pgs.119-120).*
>
> *Also:*
>
> *"There is nothing unphysical about functional entailment. What is true is that functional entailment has no encoding into any formalism of contemporary physics; it represents a notion of final causation that is unencodable in any such formalism from the outset. On the other hand, it reflects basic features of material organization per se." (Rosen, 1991b: pg. 134).*

It is tempting to think of the relational view as merely instrumental or complementary to the physical/mechanical perspective; but this would miss the point that through the study of living systems something fundamental about nature itself has been discovered that can inform even physics. Such deeper philosophical implications add relevance to the way we value nature and express those values though ecosystem management and policy, and through ethical and social dimensions that may include human values alongside other natural functions (see Chapter Five). The purpose here is to apply this deeper view of nature to the design of ecological informatics; to entail informatics as closely as possible to Rosen's modeling relation, presuming that will be a better representation of living nature.

The approach also applies to ecosystem management and its integration with ecology, which has become an important aspect of policy in recent years (see Chapter One). Ecosystem management is, by policy, "science-based," and it is obviously meant to *decode* certain actions into system change. In this way every model, human or otherwise is potentially effective through its application in management, policy, and decision making. Even human values drive certain ecosystem changes. Both natural and human models are thus realized (or actualized)[10] in nature or human society, and a general theory of complex relationships applies equally to both. All system-dependent functions are thus assumed by this theory to be causally effective, as are general physical laws, but with local origin and control associated with the organism. This applies to both adaptive and cognitive functions. Modeling relations thus represent a holism in which nature models itself providing a local semantic context. Furthermore, organismic models, because they come with organisms, impart this quality to ecosystems, and human models impart it to social, political, financial, and religious systems. Each of these systems may also have pre-organismic entailments of their own, i.e., the beginnings of semantic closure as suggested in studies of "ecological memory" (Peterson, 2002). Natural models constitute a "fuzzy" or imprecise specification for future conditions, meaning that due to the complexities involved, the future outcome is not uniquely determined by presently observable conditions. Such relations can obviously be multiple, implying multiple potentials for change, or they can be viewed in terms of system "attractors," similar to those proposed in chaos theory (Kay, 1997).

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[10] Rosen employs the word 'realization to refer to the process of a model becoming manifest in a natural system. I prefer the term 'actualize' because I consider the models equally real in a pure sense.

We can now see that relational complexity may be understood as arising from the natural incompleteness of information inductions—the means by which nature copies, or mimics, itself (which is entirely analogous to the means by which we do science). This can be seen in the relationship between internal model encoding (through evolution, development, or learning), and decoding (through behavior and biological processes). Every system interaction, through both measurement and functional expression, involves a *pattern*, which is a mutual encoding of incomplete information between systems abstracting (taking away) some partial or reduced aspect of the system interacted with. Each interacting system, by virtue of its own induced pattern, describes the other system in some partial way derived from the interaction. For example, quantum particles can become mutually defined as an "entangled" pair, each encoding specific aspects of the other; the exact pattern of forest blowdown encodes specific information about the wind; over evolutionary time information about the seasons becomes encoded in plant phenology; higher organisms are capable of learning from experienced or observed patterns; the moon encodes a pattern of feelings in lovers on a warm night. Such encodings comprise measurement patterns of natural systems that are implicit in some kind of interaction. If the encoded pattern is stored in a way that allows it to be applied in later interactions, and to the extent that these encodings reflect regular patterns in nature, they build models that produce anticipatory behavior. Such models, implicit in nature, constitute a relational ontology, in which natural systems can be seen to interact by mimicking each other (i.e., considering the formal system in Figure II-2 also as a natural system).

This description of relationship may be taken as defining what is meant by *interaction.*

Escher's Analogy

An analogy to the idea of mutual encodings in a modeling relation can be seen in the famous sketch of Escher, of two hands drawing each other (**Figure. II-3**). The implicit complexity is what intrigues us about this image. The drawing implies that two systems can be mutually and simultaneously defining. That the resulting image has no precedent in the material world, and is therefore not a mere mechanical reconfiguration, but instead emerges out of the relationship itself, is precisely the intrigue. This is indeed the implication of the modeling relation, where chicken-egg causalities are its characteristic. In fact the analytical strength of relational complexity is precisely in its ability to represent such causal loops, which in mathematics are known as impredicativities.[11]

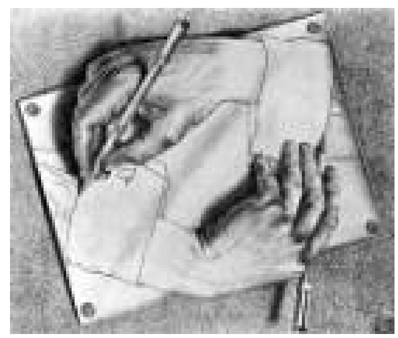

Figure II-3:
"Drawing Hands"
(©The M.C. Escher Foundation)

One can also see, using Escher's diagram as an analogy, that if there are influences from the environmental context, say the lighting in the room, that this will induce some change in the result by influencing what is being drawn, or encoded. Rosen points out that the encodings do not exist in either system being related, but in the "ambiance" or environment—the larger system that contains both. In this way the

[11] 'Impredicativity' refers to the condition where a formal specification of behavior is not based on immediate environmental inputs, i.e., they are not *predicated* on immediate external context; but instead are a response to internalized causes. In mathematics 'impredicativity' refers to closed inferential loops. Rosen explained in *Life Itself* that these were, as much as possible, expunged from quantitative mathematics and mechanistic science precisely because their result cannot be generally specified.

entailments are connected holarchically[12] with greater contexts and constrained by them.

The incomplete nature of abstractions (the act of drawing in this case) and their modification by contextual influences (the lighting, the canvas), would lead to an unpredictably changing picture, allowing for self-organization, adaptation, and evolution (Kineman, 2002). For example, an organismic function such as reproduction, can itself be altered by ecological relations that are contextual. This is analogous to changing the lighting in Escher's drawing. This means there are contextual influences on how a function can be expressed in environmental or geographic space. Those differences feed back to the function's definition. The result is a mutual definition that can be attracted to some optimum or could produce instability depending on the nature of the feedback. Combine this with other contextual relations and the picture becomes quite complex and unpredictable, but in realistic ways that can be focused in the analysis on those phenomena the scientist chooses to examine.

Causality

From the above, we can see that complex behavior arises from life's ability to entail efficient (process), formal (model), and final (semantic) causes, from DNA to mental constructs (referring here to Aristotle's four types of causal explanation as discussed in (Kineman, 2003a)).[13] Formal and final causes are implicit in the

[12] Holarchies are different than hierarchies in that their relations can bridge levels (Kay et al., 1999)
[13] Rosen stated on pg. 144 of *Life Itself* (Rosen, 1991b) that a material system is an organism *"if and only if it is closed to efficient causation."* This implies that formal and final cause will follow from contextual relations. On page 245 he refers to the *"crucial idea of* function*"* associated with *"a perfectly rigorous notion of final cause."*

ontology established by modeling relations. Organismic models embody functional specifications encoded from a hierarchy of historical and present relations to drive fabrication, maintenance, and behavior. As Schrödinger realized, the key difference between living functions and those of the physical world is that living functions are causally entailed from within.

Organismic functions imply their own local "laws," precisely because they are entailed inside a causally closed system. Local and unique, these system-dependent laws constitute internal predictive models, just as general laws provide general predictions. For example, there is no general law of physics that dictates a drive for seasonal change in plants. Because of adaptation to environment, however, plants have generated and incorporated such a law that is unique to the system that generated it (Rosen and Kineman, 2004). Organisms are thus presumed to operate in this manner, making unique models of themselves and nature and expressing those models as functions. In a sense, each organism lives in its own universe of laws that are general only for that system. This is a logically valid form of final cause and anticipation. In a sense, functions under ecological control constitute intentions. Rosen thus considered living systems generally to be "anticipatory systems." The process need not be cognitive or self-aware; nevertheless, the existence of anticipatory models in an individual or an ecosystem represents implicit potentials, which together constitute the domain of adaptation and evolution.

In keeping with the definitions above, a function is an information induction between a model and changes in observable conditions of a natural system. Mechanistic theory also conforms to this view, but for a very special system—a general system comprised of pre-determined states. These laws appear to exist outside of, or prior to, nature precisely because they are frozen in history. They are part of a universal system of actualized states in the same way that biological functions are part of the living systems that generated them. The whole problem of complexity arises when we try to explain the present, which comprises many possibilities, from a study of its history, which was only one of them, unless we are assured, e.g., by mechanistic constraints, that those historical patterns will repeat themselves. Surprise is therefore to be expected in less constrained living systems.

To summarize, relational theory allows one to consider causality inside natural systems, which placement explains their complexity and life. It presents change as the action of system-dependent functions, in a continuum that can range from semantically (causally) causally closed local entailments (organisms), to less closed ones (ecosystems), to completely general ones (physical systems). While the modeling relation can be taken as the basic building block of natural entailments, it, and self-similar decompositions or aggregations, are not empirical concepts, they are ontological. We must next determine the appropriate empirical terms for studying and representing modeling relations.

Rosen emphasized that in systems biology, the *"functional component"* should be the fundamental unit of analysis (Rosen, 1991b pg. 120). There are examples in ecology and information science of representing functions directly in informatics. A promising start was made in ecological informatics capturing "Key Ecological Functions" (KEF's) of wildlife and ecosystems in the Pacific Northwest (United States and Canada) (Marcot and Vander Heyden, 2001). This work supported functional analysis, looking at the supply and demand of key functions and how this relates to system stability and critical resources. These and similar approaches require a theoretical underpinning, without which alternative instrumental approaches may be too diverse for any to gain wide acceptance. Rosen's relational biology could provide the needed foundational theory, focusing on a practical concept of the "surrogacy" of functional components, as reflected in Marcot's informatics, providing a more practical alternative to more extreme (perhaps rhetorical) ideas such as *"functional equivalence"* (Hubbell, 2005).

Structure-Function Epistemology

It turns out that the encoding and decoding information inductions of Rosen's modeling relation can be identified with the concepts of *structure* and *function* emerging directly from the modeling relation as the primary empirical elements of relational theory (**Figure II-4**). There is, accordingly, a direct translation from the ontology to the epistemology, which Rosen defined respectively as "w*here the system came from*" and "*as it exists,"* aspects that each has effect in a complex world (Rosen, 1999: pg. 281). In this translation, structure *is* the encoding itself and function *is* the decoding itself, both as information components. Their connection in a given system defines a natural component, drawing its identity from the

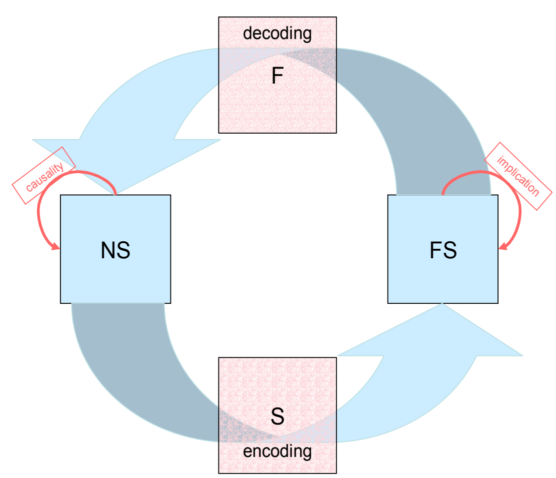

Figure II-4: Structure (S) and Function (F) emerge from the modeling relation underlying ontology; modeling relation itself. Structure, function, and identity therefore comprise the epistemology,[14] and thus we have the empirical elements needed to represent Rosen's relational complexity in an information system. This translation provides a rigorous definition of these terms. Rosen described the *"structure"* of a system as *"what it is"* or *"what it is made of"* in terms of a system of measurement; and the *"function"* of a system as *"what it is for,"* or "*what it does...in another system"* (Rosen, 1971; see also Rosen, 1973). These statements seem to correspond with popular use, but their definition as information entities existing between a system and a surrogate system, casts them in a new light. In particular it is not common to remember that both structure and function <u>require</u> context and are defined by their role in a context (the measurement context, or the context of that which is measured).

Structure thus refers to material arrangement in terms of biotic and abiotic components that can be observed and on which measurements can be made in space and time and on which models can be formed. *Function* refers to that which produces (or by which we explain) measurable change in a realized material system. Hence structure is defined within a functional context (abstract measurement) and function is defined within a structural context (realized behavior). Putting together the various descriptions (Rosen, 2003b: pg. 188), we can say generally that structure is the *material effect* on the laws of biological and ecological behavior (model encoding),

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[14] Structure and function may be related, with some effort, to Aristotle's *energeia* and *entelechia*. E*nergeia* means "being at work" which implies presence and activity in nature, as an actualized system ('structure'), and *entelechia* is "being at end," which implies a specification and attraction or drive for change, as a potential of nature ('function' or even 'purpose' when contextualized). (Sachs, 2006) (see http://www.iep.utm.edu/a/aris-mot.htm#H2) Natural law is thus replaced by system potential, but they are still equivalent in the general case.

and function is the *behavioral effect* of those laws on material systems (model decoding). The physicist Chaisson, for example, attempted to attribute the ontology of even physical law in the apparent early universe to the properties of interaction between primitive elements of matter and energy (Ulanowicz, 2007).

As effects, structure and function are translational across systems; that is, they may encode from and decode to both *Self* (the structure-function "component" that is whole) and *Other* (components interacted with partially, as structure or function). By being effective across systems, structure suggests *possible* function and function suggests *possible* structure. Another way to state this is that when a natural system is encoded into a model, it is done by means of 'reading' the structure into a system model, which simultaneously establishes the possibility of its decoding into a natural system, i.e., the execution of the function. Likewise when a function alters a system, a new structure has been formed, creating the possibility of new functions. In this way, *possibilities* become natural as a result of structure-function linking across interactive systems.

Encoding, which we perceive as *structure*, is the result of measurement. Measurable states are really *percepts* (Rosen, 1978); objects are inferred entities. If we relax the mechanistic notion that states correspond with pre-defined material objects as such, it is then natural to associate our idea of structure with encoding.[15] *Structure* thus comprises the implicit object of state measures within a measuring system (inside), whereas *function* comprises the implicit subject of behavior

[15] This does not contradict the notion of classical objectivity as it is evident in the physical world and everyday experience. It provides an ontology for such objectivity in prior interaction (or measurement), as proposed, for example, in recent research on quantum decoherence (Schlosshauer, 2004).

expressed in an ambiance (outside). Both are empirical concepts that emerge from the ontology (the modeling relation) as epistemological complements. *Structure* can be inferred directly from observation and *function* can be inferred indirectly by experiment. As inverse aspects of each other, together they constitute a natural, always active process of mimetic communication between interacting systems. Hence these definitions do not beg the question of why there is a relationship: The terms themselves are defined as activities, not objects, and thus account for autocatalytic 'vitality' of the system.

Accordingly, *structure* is never static in the sense of a 'thing;' it is active in the sense of dynamic behavior. Neither is function ever inert in the sense of a 'sign' or symbol (that requires another system to apply it); it is active in the sense of an attractive or selective potential that is self-executing. There is no need to consider if a potential may be activated or not. It is it always active, as a tension on the natural system, it attracts change in balance with other such tensions. The combined effect of many potentials may then account for regulation.

Organismic functions, which must be expressed through organismic behavior, also define ecosystem potentials. For example, the ecosystem function of providing tiger habitat is in part a result of ecological potentials that may drive system change in various ways, perhaps attracting tigers or even evolving a functionally similar organism. Being in part biological, it is also subject to adaptation. Likewise, functions that the tiger performs have ecological effects that modify, select, or otherwise attract certain aspects of the ecosystem structure. The result is a mutual attraction toward some functional state that becomes co-defined by organism and ecosystem. Such potentials should be considered real in the same sense as physical forces because it produces measurable change, but it is highly mutable. The ecosystem, in this sense, "anticipates" tigers; and tigers anticipate, seek, and, may participate in the construction of their own niche (Odling-Smee, Laland, and Feldman, 2003).

Functions become semantic (meaningful) with regard to their role in context. For example, "pumping blood" is a function of the heart in relation to the human body. Pumping blood has meaning to the overall life of the organism, which is why it is subject to adaptation. We cannot say that a quantitative improvement in pumping blood confers adaptation; it is only its qualitative effect on the overall life of the organism that relates to selection. In this way it is clear that the semantics, i.e., what a function means, is just as causal in a living system as its structural syntax, i.e., how it is arranged. It also appears that *meaning* is a transition from quantitative to qualitative logic; from numbers to categories. There are material and efficient entailments (the physiology), formal entailments (supply of nutrients, oxygen, and other services as part of an overall plan of survival), and final entailments (accomplishment of life's objectives). Such functions can obviously be co-dependent and latent; that is, under system controls. Most importantly, organisms are comprised of *"metabolism-repair (M-R) systems"* (Rosen, 1958a) which make them self-sustaining and adaptive. Adaptation involves positive and negative feedbacks, thus selecting ecological functions that tend to establish synergies in the ecosystem context (Corning, 1983). For the same reason, implicit ecosystem functions will attract organisms that can actualize them synergistically. We can see in this arrangement the appearance of apparent intention[16] purpose (telos)—Aristotle's controversial "*final cause*," as attractive potential. The idea of potential suggests a system poised for action.

Rosen's Formal System, as carrier of previous encoding, implies that the process of decoding is a functional application of a natural model—a natural specification of possible conditions. Decoding thus involves an induction of change in a natural system. In the analogous case of a scientific model the induction is in a surrogate system (e.g., a computer output) used to compare model predictions with nature. Pursuing the analogy between formal and natural entailment, we might then think of natural functions in an analogous manner to mathematical functions, in that they are operators that, subject to contextual regulation, change what they operate on. Indeed, modeling is about the congruency of natural and mathematical functions.

As we saw in Figure II-4, above, *structure (S)* and *function (F)* are related to each other through the same ontological relation that exists between natural systems and natural models. However, because they are now part of the empirical world another relationship is implied that relates specific structures and functions as part of a realized component. This implies two kinds of bi-directional relationship, that which is part of the realized component, which I will call the *direct* relation, and that which represents potential structure-function pairs, which I will call the *indirect* relation (Kineman, Banathy, and Rosen, 2007). In both cases the relationships involve the operation of a function on states and the performance of a function by the structure. These relations are diagrammed in **Figure II-5**, where the straight arrows represent the direct relation for realized structure-function pairs, and the curved

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[16] Perhaps etymologically related to the work "tension" referred to earlier. '*Intension'* and *'intention'* today refer to physical and psychological potentials, respectively.

arrows represent the indirect relations for structure-function associations that exist as potentials.

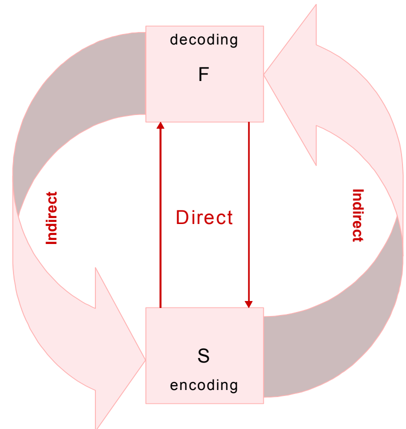


Figure II-5: Direct and Indirect Relationships between Function (F) and Structure (S)

We may thus associate function with structure by means of two types of information relation, which I will call *"direct"* and *"indirect."* The *Direct* relation refers to a realized component and involves change that a natural function is responsible for in the material structures it operates on, limited by contextual constraints on the system producing the function (the form that carries it, such as an organism or taxonomic group). It involves what a function will do (i.e., the change it prescribes) when expressed in a domain of action (the organism itself or the ecosystem) and under the adaptive constraints that domain imposes on the structure-function unit. The *Indirect* relation implies a process of mutual selection or adaptation (analogous to system attraction) between material structures of a living system and their possible functions in various contexts. It is a structure-function decoupling, where multiple functions can be associated with a given structure (component or ecosystem) and multiple structures can be associated with a given function. In this way we can describe how function attracts or selects structure through migration, development, or evolution, and how structure acquires various functions in relation to other systems, including context. Thus the process is mutually constrained: The possible functions are constrained by state-space and the possible structures are constrained by function-space. These epistemological relationships are all necessary to represent the complex ontology of the modeling relation. For example, the functions that a bear can perform are constrained by organismic adaptation whether these functions are performed by a bear or something else. They can be described either generally, as a function of the environment, or specifically for each organism. *Indirect* and *direct* information relations correspond to the prior terms "*referential"* and *"non-referential,"* (Banathy, 1999; Kampis and Rössler, 1990). Banathy also mentions *"state-reference"* information which is the reduced case of non-referential information, or mechanism.

The Niche as System Control

The constraint of a function by its structural context, or the constraint of a structure by its functional context, can each be expressed in a completely analogous way to the ecological niche, employing the 'n-dimensional' niche concept (Hutchinson, 1953), but as a completely general specification of structure-function constraint (see Chapter Three), in keeping another of Rosen's conclusions, that "*niches have effects"* (Rosen, 2003b: pg. 199). Niche relations can thus be used to represent Corning's idea of control information (Corning, 2001), because they represent regulation of functional expression and structural selection, and together balance multiple regulatory potentials of the overall system. Such models can specify the degree to which any structure or function may be expressed within a controlling or limiting context. In niche models, the context (environment) is defined by the theoretical dimensions of a hypervolume in an adaptive space, and the controlling effect of these dimensions is defined by the correlation between the expression of structure or function by a living system *component* and its limiting variables on those dimensions,[17] i.e., the *response function.*[18] The niche model can then be translated into geographic coordinates according to the distribution of the limiting variables. In theory the niche may be specified on general principles that allow it to be applied at any scale or to any system or any kind of functional or structural suitability (assuming we understand how the chosen system responds to limiting variables).

The direct relation discussed above involves association of a specific function with a specific structure, such as an organism or species. This kind of relationship corresponds with traditional applications of the ecological niche concept, and unifies the two primary interpretations of the ecological niche: that of *resource requirements*, and that of *function performed* (Liebold, 1995). Indirect relation makes the former less deterministic than the terms 'requirement' and 'performance' might imply by allowing for two-way surrogacy from functional and structural attraction and selection. This process can also be represented using general niche models. The overall bi-directional relation can be modeled as a selection or optimization of overlapping niche model alternatives (see, for example Marcot and Vander Heyden, 2001), weighted by relative indicators or assigned empirical probabilities.

As an example, organismic functions involving the consumption of oxygen and production of CO_2 can be described and constrained by niche models that are directly associated with each organism and assigned relative strengths or probabilities. Organisms comprise the ecosystem and establish its character. Therefore, the combination of such models would constitute an overall functional

[17] Those measures of the environment across which the degree of expression of the structure or function varies for theoretical reasons.
[18] Meant here in the mathematical sense

requirement of the ecosystem (biological oxygen demand). Organisms that produce oxygen and consume CO_2 support this system, and to the extent that suitable conditions for them exist, there would be a synergistic exchange.

Overlapping niche models can thus describe the mutual attraction and implicit ecosystem functions in terms of life-sustaining conditions enhanced, through organismic and ecosystem feedbacks. In this way, the system defines the individual fitness for various structure-function combinations and their relative strength or presence establishes the characteristic relationships of the ecosystem. It should be clear that *indirect* relation relationships are quite fluid in the ecosystem, depending on the level of surrogacy that is available, whereas *direct* relations are those actualized at any given time. One can see in these complex relations both the opportunity for further organismic evolution and the ability of ecosystems to self-organize and self-stabilize around various synergisms.

Relational Communication

The information encodings and decodings in Rosen's modeling relation, which are accessible to us as structure and function can now be put together into a theory of communication suitable for general informatics design. Multiple structure-function relations like the one in Figure II-4, above, are infinitely connectible like molecular bonds. **Figure II-6** shows the basic way in which structural and functional elements can be combined. As shown, the analysis can be done looking at either the functional aspects of a system, A, or its structural aspects. Both communicate to other systems, and both have structural and functional predicates in their own system. The same, of course, is true of system B. The area of overlap in the diagram is the set of shared structures and functions on which communication takes place. There are, of course, vertical entailments in each system and their overlap, since structures and functions do not occur alone, and hence a third system is thus implied by the relation of any two. Depending on how we query the relations, we could set up the model so that the common S-F system in the middle represents species that connect both systems, for example, system A as a range ecosystem and system B as a human ranching system. The structures and functions imparted to the human ecosystem are then specific ecosystem *goods and services* (Chapter One) and activities in the human system clearly have feedbacks that affect their different meanings in each of these systems. High production in system A, for example, perhaps a result of range management in system B, might mean prosperity in the human system B at the same time that it may mean overproduction and future crash in system A.

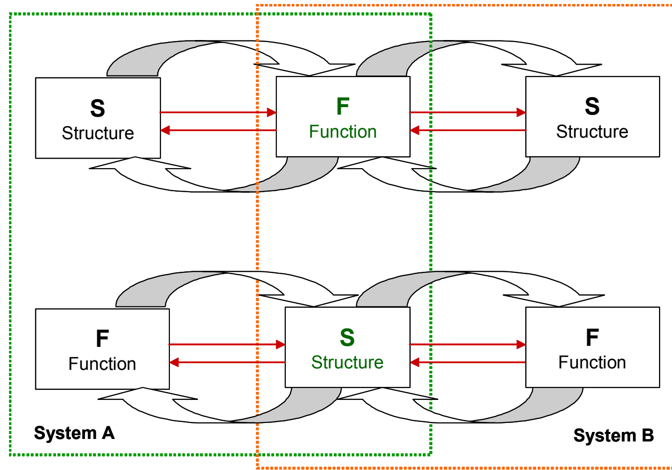


Figure II-6: Complex Communication via Structure (S) and Function (F)

Figure II-7 shows a more explicit example of a relational pathway that might be involved in coupling an ecosystem (system A) and an agrarian society (system B) via climate. The specific elements in the diagram are presumably the ones of scientific interest at the time, their defining parameters being drawn from the informatics enterprise system storing state data and behavioral inferences. This

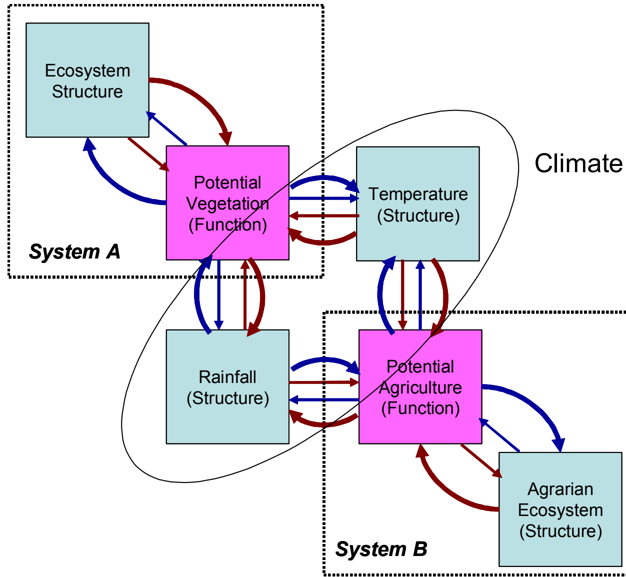


Figure II-7: Agro-Ecosystem Model

example involves six structure-function relations, two explicit data sets (for temperature and rainfall), and two functions (for potential vegetation and potential agriculture) that operate on and are constrained by the structural elements in the model. The functions might be represented by a state transition models which alter states in each system under the constraint of niche relations, as discussed above. The arrows indicate direct and indirect structure-function relations. Obviously both functions are themselves complex, involving components with their own complex functional relations. At this level, the model aggregates the sub-components, and information required to complete this schematic as a information query or system model may come from similar aggregation of data and models stored about the sub-components or from data and models stored at this general level. Both the niche model and the function model can be stored in an informatics architecture such that they can be applied according to the indicated entailments. The niche concept can be generalized for this purpose, allowing it to represent any kind of function (i.e., biological, ecological, social, or physical) (see Chapter Three).

There is nothing ‘emergent’ in figures 6 or 7; all structures and functions are part of natural systems and all may be represented empirically, but they are co-defined by system relationships and shared by multiple systems. This way of describing natural communication between systems or components of a system is perhaps analogous to a mathematical expansion, allowing a system to be analyzed in terms of structure-function relations that are proximal to a given phenomenon of interest, and allowing less significant terms to be omitted. The holarchical nature of modeling relations (discussed earlier) suggests that many relations are best seen as contextual. Functions may accordingly be identified with taxonomic components and sub-components, such as species, to explore their relationship with the environment and ecosystem, or with more broadly defined ecosystem functions. A contextual hierarchy can be represented as a series of relations comprising new components or sub-component definitions at any level. Functional decompositions can be individually modeled or assembled in terms of more inclusive functions, or 'function*al clusters'* as shown in **Figure II-8** (Christian et al., 2005), to represent concepts like *ecosystem services*. As suggested earlier, relational analysis also applies to material systems and the same structure-function epistemology can be used as an alternative to describing them mechanistically. These two forms of analysis are in theory equivalent descriptions for any system that is in its entirety a non-living mechanism; however, by using relational analysis we can

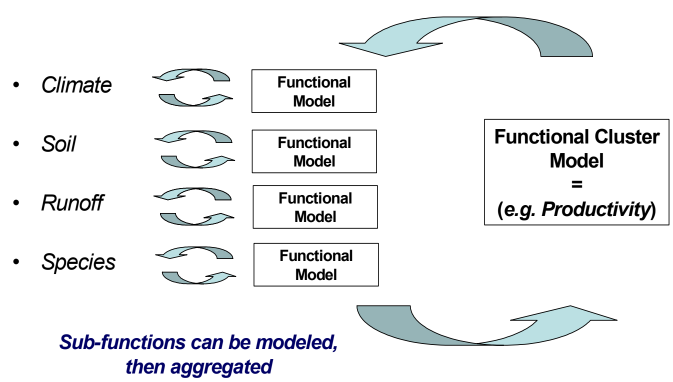


Figure II-8: Functional Clustering

describe systems that have both living and non-living components that are important in the analysis (which will most often be the case).

For example, even a seemingly mechanistic element of the structure of the environment, temperature as in Figure II-6, can be represented as a complex aspect of the environment, thus allowing the model to easily add the consideration of surrogates in the same way they are considered for organisms. A surrogate for atmospheric temperature as a structural element in this case, might be coal pots or plastic covers, commonly used in agriculture to prevent freezing. The various additional functions that such substitution implies (or requires) can also be added, and so on. In the case of a strictly material structure, however, functional and structural replacement is under the control of an external system. This does not change the analysis, but it adds the ability to specify the controls more deterministically in those cases.

The functions produced by a physical structure are the ones we can describe by general physical laws. To a certain extent certain biological functions that appear with considerable regularity and generality across known systems, might be represented by mechanistic equations if one is careful to annotate that assumption. In this case the complex architecture can prevent one from overlooking possible complexities by attributing the relation appropriately, and by always being extensible to the addition of more complex relations when they are discovered. The use of mechanistic descriptions for sub-components of a complex informatics is a practical and necessary compromise; but it is a safe one if the architecture has the elements described here. While it may even be true that all components might ultimately and theoretically be decomposable into computable ones (as computational complexity assumes), relational theory tells us that even allowing for possibly different physical laws within each domain having semantic closures, the result would still be an infinite set. The relational analysis remains parsimonious where complexity is an issue, whereas mechanistic representations are parsimonious and expedient where we are certain it is not. Clearly, then, the art is to know when reduction can be afforded by one's question, and when it cannot. Indeed such reduction can be done experimentally and it can aid decision making by mapping map out a range of possible outcomes, or alternative futures, and these might be assigned theoretical or empirical probabilities to recover some of the natural complexity. This compromise bridges the gap between relational and computational complexity methods, allowing us to employ dynamic models where they can be assumed to be non-complex.

Implications for Eco-Informatics

Implementation of the structure-function architecture described above would allow information queries in the normal sense, but more usefully following known relations, retrieving state-based information as well as associated behaviors, along with important information about the effect of context. It would also allow experimental models and simulations to be constructed by iterating each loop in an appropriate experimental sequence, while considering functional and structural change (adaptation or substitution). Most importantly it would allow analogies to be explored as a means for acquiring information about a system that cannot be gained from that system itself in real time. Such analogy may help reveal characteristic behaviors and possible conditions not predictable from initial conditions, such as attractors and possible 'tipping points,' so critical to ecosystem management. Having the data and functional representations together in the informatics system would allow any user to develop a simulation or analysis for scientific or decision-making purposes. Queries, models, simulations, analogies, and other forms of analyses could be conducted across systems and across scales, helping to resolve a major issue in ecological integration (Wessman, 1992).

I wish to emphasize, in keeping with the general theme of this discussion, that the fact that function must be inferred from observation and experience does not mean that an observational database is all that is needed in informatics. We should represent the functions directly for three reasons: (1) Inference involves a good deal of intuition and first-hand experience with the subject and its context. Field work and careful experimental design is generally involved. Understanding ecological functions comes with involvement and experience. It can be more difficult to capture all the contextual information and personal experiences required for someone else to reconstruct a given inference later, from the record, than to record the inference itself—the inferred function—as a consequence of experiment. (2) There are many different functions that can be inferred from a given structure, and vice versa (Rosen, 1973). (3) By representing both structures and functions (data and models of elemental functions) in the informatics, we can also capture and represent the relationships by which they define complementary wholes. This provides a much greater level of knowledge than is possible by presenting structure and function separately.

It is axiomatic that prediction will be limited by complexity, for if we accept indeterminism at the root of complexity, even an exact duplicate of a natural system would not follow it precisely. The goal is thus to provide information that is as close to nature as possible. While structure-function relations can be used for complex analysis, and simulations, they serve a more basic purpose in retrieving basic information without the loss of natural context. Simple information retrieval through these relational links can help one see the associated factors in a given problem, even if some of the information is only descriptive.

The ability to describe complex entailments without getting lost in an *"infinite regress"* of mechanisms (Rosen, 1991b: pg. 247; Rosen, 1999: pg. 16) is the essence of this approach. In a relational analysis, we define each element of the decomposition (or composition) as a 'whole' unit that is itself complex, whereas no finite series of mechanisms can accomplish this. In doing so, we sacrifice the ability to reduce these models to one model, but instead combine their effects or potential effects in the natural system. The effects can be combined because they are being expressed in the general system, which is a self-consistent, measurable, and computable domain. This achieves composability and decomposability in the analytical method without reducing the components to mechanisms—one combines effects, not causes.

One may thus model proximal relations while not losing complexity or the ability to explore more distant relations and how they propagate (as in 'butterfly effects') or are damped by the intervening feedbacks. In this way a model can be tuned to those relations one wishes to examine. The results of query or modeling can itself be stored and made available for further analysis as needed, to determine common patterns or perhaps analogies with similar circumstances, or to produce scenario-driven simulations. In fact, C.S. Holling's idea of *"adaptive management"* (Holling, 1978) implies just this proposal, that functional effects of management should be considered part of the system that we wish to comprehend and model. In the system concept presented here, physical systems, ecological systems, human management and even values can be represented in a relational analysis.

Critiques and Confirmations of the Theory

Critics of Rosen's view claim that the ontological aspects of the theory—the assumption that modeling relations exist in living systems themselves—are unnecessary, and that one can arrive at the same end using mechanistic terms. This argument agrees with the philosophy of von Neumann, who more or less founded the field of computational complexity (see: Konopka, 2007), as well as the fields of artificial intelligence and cellular automata, and also defined the architecture used in most of today's computers. Von Neumann thought of mind-body dualism (*"the epistemic cut"*) in terms of the distinction between *software* and *hardware*. More recently Pattee, following von Neumann's approach, proposed a view of complexity comprising *"control*" and *"selection"* processes similar in some respects to those discussed above, based on a "*matter-symbol*" relation (Pattee, 1995). In contrast Rosen's view of the mind-body problem is precisely his modeling relation. Pattee claimed that the Von Neumann approach and his own were equivalent to Rosen's in the end, but Rosen strongly disagreed with this assessment. The Rosen relation has also been referred to as "*the Hertz-Rosen relation"* (Konopka, 2007), equating it with a modeling relation proposed much earlier by the brilliant classical physicist Heinrich Hertz (who developed the foundations of wave mechanics for propagation through a physical medium).

It is highly inappropriate, however, to conflate Rosen's concept with the earlier ideas of Hertz and von Neumann, or the modern ideas of computational complexity; first because they are not related historically, and second because they are diametrically opposed epistemologically. In fact the difference in views defines a major split in complexity theory between computational and relational views. Hertz indeed proposed a modeling relation, but consisting of two dynamical mechanisms, one in nature and the other in the mind. He wrote:

"The relation of the dynamical model to the system of which it is regarded a model, is precisely the same as the relation of the images which our mind forms of things themselves. ...The agreement between mind and nature may therefore be likened to the agreement between two systems which are models of one another, and we can even account for this agreement by assuming that the mind is capable of making actual dynamical models of things." (Heinrich Hertz, quoted in Grasshoff, 1998)

Hertz was a brilliant classical physicist who opposed Newton's idea of forces, on the grounds that they were too metaphysical and that nature had to be a materially interconnected fabric in which dynamics were the result of direct *"connections"* between material *"points"* of the ether, which was commonly accepted at the time. His approach was thus firmly mechanical with no hint of the mutual causalities Rosen would propose later. Grasshoff summarized Hertz's view thus: *"The material points* *of the Principles of Mechanics are paradigm cases of simple objects in the world, which by different configurations make up all possible facts of reality."* (Grasshoff, 1998)

Rosen strongly disagreed with the mechanistic assumptions adopted in these prior views, on the grounds that they cannot account for self-entailment, and therefore offer no explanation of origins. As such, they cannot lead to the appropriate epistemological terms for analyzing complex living systems (Rosen, 1993; Rosen, 1999: Chapter 6). He particularly challenged von Neumann's idea that complexity can emerge from mechanism at some threshold number of interactions. Rosen's deeper ontology does not require such a threshold, nor does it separate hardware from software or matter from symbol; these concepts appearing separable only in mechanistic analysis. Because the Von Neumann-Pattee approach was to translate each side of a modeling relation into epistemological concepts directly, it necessarily fractions the unit that Rosen said must remain whole in a complex analysis of nature. Rosen's was thus a completely different kind of analysis, decomposing or composing systems into other whole relations rather than fractioning them.

Nevertheless there are strong feelings among many scientists that the ontological issues need not be investigated. Pattee specifically eschewed the ontology of his *matter-symbol* relation (Pattee, 1995) claiming, perhaps in the tradition of Kant's *Critique of Pure Reason*, that there can be no verifiable natural argument for ontology, and therefore it can have no effect on science. His *matter-symbol* dichotomy provides terms that are compatible with the mechanistic concept of discrete states and thus the idea that nature is computable. Rosen, on the other hand, argued from the less popular position, that biology must involve consideration of the ontology of nature because organisms themselves appear to involve ontology; *their own*. In other words, living systems, internalize causation itself thus generating unique system-dependent laws. In particular he claimed that their *"metabolism-repair (M-R)"* functions are *"closed to efficient cause."* Rosen thus challenged claims of artificial life based on von Neumann's *'universal constructor'* (a logical machine that von Neumann claimed could produce open-ended evolution) or similar computational schemes, on two principles: First, that *computation* cannot count for *construction* in the natural world, and second, that it is logically impossible for a machine to incorporate its own causes because it is, by definition, insufficiently entailed. The process of "realizing" a model (or formal system) in nature cannot be described as a mechanism without implying an infinite regress of causal systems in the attempt to represent the system's origin (Rosen, 1991b: Chapter 10). This, to Rosen, was a clear sign that the living or complex system ontology is general to the mechanistic ontology, not the other way around. Also standing in contradiction to any claim that mechanisms are general, is the requirement of mechanism that some form of *natural law* must be prior to empirical events. Rosen asked, what entails the laws? In other words, a flaw in Kant's critique may exist in the assumption that nature does not produce or constrain the laws we discover about it; that they must necessarily come from outside of nature. As a consequence laws must be considered complete, fixed, and perfectly general. It follows that measurements must correspond with some notion of a prior material object on which states are measured. Such 'objects,' 'natural laws,' and their inexplicable origins constitute a default mechanistic ontology—the reality of states, universal laws, and local space-time coordinates. Science is no longer restricted, however, to the view that limits to knowledge allow only the study of pre-defined sensory objects, by sensory means and therefore nature as comprised of states. Perhaps the main accomplishment in post-modern scientific philosophy has been to shatter that tautology.

Rosen claimed that life involves systems that are *"closed to efficient cause,"* and that such a condition can be described in the mathematics of category theory, in which mechanism is a special case. While Pattee also claimed that "*semantic closure,"* or self-causation was possible, he attempted to derive it from mechanistically defined elements—*matter and symbol*—or von Neumann's *hardware and software* (Pattee, 1995). Rosen's description of a closed causal system in category theory (**Figure II-9**) (Rosen, 1991b: pg. 251)[19] has recently been verified, with some further conditions, by , with the profound result that indeed there can be non-trivial functions in nature, associated with the origin and maintenance of living systems, that are substantially identical to their own range and domain, i.e., there are functions, f, such that f(f) = f (Rosen, 2003b: pg. 10)[20], where f acts as function, argument, and

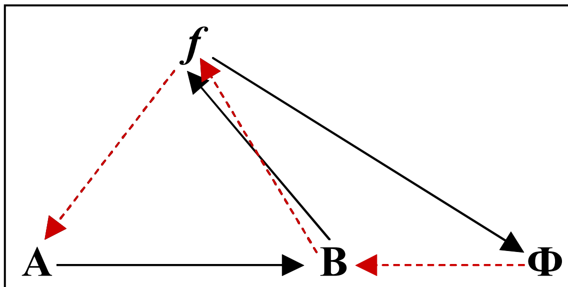


Figure II-9: Efficient Closure (self-entailment). Dashed red line indicates functional expression (decoding), solid line indicates system change (encoding). *f* = metabolism, Φ = repair/reproduction.

[19] The arrows in the diagram have been re-labeled to correct an editorial error in Rosen's book
[20] Rosen wrote the equivalent form: $x^{\wedge}(f) = f(x)$

result (Letelier et al., 2006). I believe, however, that the equation should incorporate an indeterminacy term resulting from the incomplete nature of abstraction discussed earlier, writing $f(f) \approx f$, which then ensures that the relation will be adaptive and evolutionary. This point is supported by applying the structure-function (S-F) analysis described here to Rosen's closure diagram, where each node in the diagram (Figure II-9) is treated as a functional component (and therefore with S-F analytical decomposability). The interesting result of that is shown in **Figure II-10**, where the specific S-F connections are drawn (== and || connections refer to direct relations and the arrows indicate indirect relations, as discussed above). Where S is acted on by a function (F), the resulting change is indicated in the diagram as a solid arrow transforming the whole component into another component. Since a component always constitutes an S-F relation, a new F is thus implied from the change. An interesting and speculative result of these mappings is that there is an S and F (shown in red) left without an indirect referent (i.e., without induction into or from another component in the diagram), meaning that an S-F pair is implied that is not transformed by internal entailments and that does not act on internal structures. This might suggest that the diagram could be closed, equating A and Φ. In fact both interpretations might be valid, where the relation is completed by internal and/or external selection. The S of that pair comes

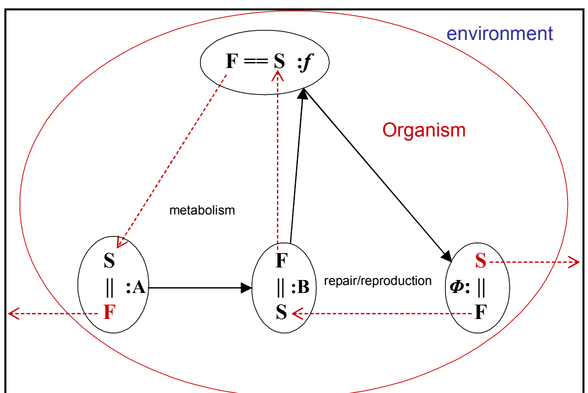


Figure II-10: Efficient Closure in Terms of S-F Relations.

from the repair and reproduction component, suggesting it could be associated with the stable structure of DNA (which in Darwinian Theory is unaltered by “acquired” characteristics, i.e., internal entailments). The F of that pair comes from the metabolism component and is free to operate on the environment. This could be interpreted as behavioral function. Interestingly, unlike Dawkins’ theory, this would suggest that behavior is more associated with the needs of metabolism than reproduction and survival, which seem more like ‘carried’ aspects of the system that then subject it to natural selection.

In any case, Letelier’s result validates the presence of loop causalities and semantic closure, and means that the mathematics associated with describing a living system as a whole cannot be restricted to the universal laws of general mechanisms. Indeed there were hints of this result in the failure of Hilbert’s attempt to derive a closed syntax for mechanisms (Dress, 1999; Rosen, 1991b), and in studies suggesting relativity of time reference in isolated causal systems (Vallee, 2000; Hameroff and Penrose, 1996). Rosen’s claim and Letelier’s proof begins a new line of research into self-generating systems that are causally isolated from the general system we perceive as physical reality.

In all, Rosen’s argument that the underlying assumptions of a theory should be questionable rests on solid ground in post-modern epistemology, wherein it was the quantum discoveries that led philosophers to accept that the exploration of ontology must be legitimate. Karl Popper, for example claimed that just such explorations, which he called “Metaphysical Research Programs” (Popper, 1959) (Stanesby, 1985) do indeed have an essential role at the foundations of science; that all science is based on founding assumptions, implicit or explicit, about the nature of their referents, i.e., the presumed reality (Balashov and Rosenberg, 2002). At the very least, we should recognize that these two forms of complexity and modeling relations come from two quite different scientific philosophies, one from a traditional computational and mechanical view of complexity, and the other from an information relational view. The first is an instrumentalist approach while the second is a quasi-realist approach (for definitions, see: Blackburn, 1994).

Conclusion

I believe we can make significant progress toward an advanced informatics approach by building a system around these presumed natural communication elements and information relations. That would establish an appropriate empirical foundation for a more integral science approach, based on complex communication and self-organization as an intrinsic phenomenon in nature and society (Kineman and Kumar, 2006). In thinking of information in terms of a modeling relation and its corresponding epistemology, a complete shift can be made from information as syntax (more data, contextual metadata, etc.), to information as syntax plus semantics (expressed by functional relations) that are system and context dependent.

I have argued that an explicit complementarity between structure and function emerges from the ontology of Rosen modeling relations and that these terms are therefore the proper ones for complex analysis, as opposed to any separable terms of reference that conform to the restrictions of mechanism. For this to be true it is necessary that these terms retain definitions and relations that do not limit them to mechanistic analysis. This condition is met by ensuring two criteria; first that at least one side of the relation exists outside the world of mechanistic description; and second that the relationship between the two sides is one of mutually causality, i.e., that impredicative loops be allowed in the informatics architecture. The first condition is obviously necessary to avoid the problem of computational complexity discussed above, that any finite combination of mechanisms, i.e., state-referenced entities, is still a mechanism. The second condition ensures complexity and is met by the simultaneous presence and effect of actual conditions and potentials.

I believe the necessary breach of tradition that considers system-dependent functions as real and unique as physical ones is the primary reason that theoretical ecology has had such a hard time developing. It is a reversal of the view that life emerged from a physical system, and thus a reversal of our entire concept of nature. It is instead a view that both life and physical systems emerged from materially and functionally complex systems that have the essential properties of living systems in their very foundation. What distinguishes complex systems from non-complex is the presence of internalized sub-system causalities that we can know in terms of their implied functions. Living systems are apparently established on this foundation, closing semantic definitions to the point of producing self-generating and self-maintaining systems.

Organisms and ecosystems can be represented for informatics purposes in terms of structure, function and structure-function relations, implicit of their deeper ontology in modeling relations. I have argued, reasoning from Rosen's theory, that life itself is an entailment of origins, and so complex informatics should do the same.

Rosen repeatedly made the point that mechanistic analysis is destructive of true ontological relations that consequently cannot be recaptured by any synthesis. If the complex properties of a living system are to be captured by science, analysis can only be performed in terms of relational wholes structured to capture the natural entailment of origins. The modeling relation is therefore as basic to complex analysis as space-time is to mechanics, and its preservation in the epistemological relations described is essential.

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. The essence of the proposed approach is to view living system complexity as resulting from modeling relations that are natural, and to translate their relations into an informatics system. This will allow us to recapitulate presumed natural (ontological) entailments and thus to represent living systems as complex entities.

Decisions operate on uncertainty, not certainty. Decision-makers, who are in the business of resolving uncertainty, need science to tell them what the valid uncertainties are, not what decision to make. Science for policy should therefore especially understand and represent natural uncertainty. To understand present and future ecological behavior and to make informed ecological decisions it is axiomatic that the informatics system should be capable of reproducing conditions and behaviors that govern the range of complex natural behaviors observed, even though in most cases it cannot precisely follow or predict them within that range. To do this in regard to organisms and ecosystems we must require that ecosystem informatics track functional potentials at least as well as observable conditions, and that it provide a framework (architecture) for relating them. Such potentials will best communicate with a society in search of policy and ethical guidance, because decisions are about the uncertain future, filled with these potentials, rather than the determined past that represents only one realized set of them. Indeed our challenge is to reason from the specific past to the general future.

If natural living systems are complex, then the informatics we use to describe them should represent the elements that, in theory, make it complex. Understanding that biological and ecological functions are manifestations of natural forms of models implies a tremendous opportunity for ecological informatics to replicate the natural entailment. It is possible to implement a system where the entailment of natural functions can be reflected directly in the architecture, thus providing a foundation for studying and modeling natural behavior. Unless functions are incorporated into informatics alongside data, in such natural relationship, we have only half the picture, and it is then not surprising that ecological informatics has a hard time presenting the complex alternatives on which decisions are based. This strongly suggests that the more we can entail informatics along natural communication principles, the better it will communicate in society as well as science.

Informatics presently documents the states but not the functions responsible for state transitions, which are so much a part of ecology and without which it is stripped of its original meaning. The practice of identifying Key Ecological Functions for species and analyzing them alongside traditional data about ecosystem conditions and processes, as reported by Marcot, is a promising step toward capturing this information in its original natural and scientific context, which cannot be effectively added later for reasons discussed.

The recommended approach would shift the emphasis in environmental informatics from representation of past states or even prediction of future states, to complex characterization of the present, including those aspects of nature that have been determined and those that have not. We then see nature in terms of realized events and potential events where an analysis is possible of the potentials and their effect. For decision support, just this change of perspective would shift the emphasis from automated decision-making under uncertain prediction, to mapping (in the mathematical and geographic sense) possibilities and options, as yet unrealized but possibly conforming to historical likelihoods in analogous systems. In such an enterprise, the informatics system does not replace the scientist or decision maker as a mechanistic model attempts to do, but instead it becomes a valuable tool supporting their work, even enlisting new kinds of experts, effectively enhancing the human connection to natural information and with nature itself.

Chapter Three:

Ecological Niche Models as Structure-Function Relationships

Abstract

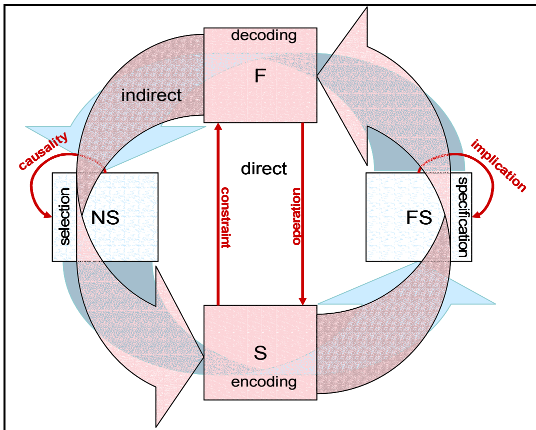
The theory of relational complexity confirms and re-defines structure and function as the fundamental empirical units of ecological analysis and provides a philosophical guideline for how they must be related to reflect natural complexity. Practical implementation of this theory to achieve a more whole and communicative architecture for ecological information requires an empirical method for representing the mutual constraints of structures and functions and their influence on each other. Ecological niche theory applies directly for this purpose. Relationships established by modeling actual and potential distributions of functions in a measurement niche-space, and actual and potential distributions of structures in a function niche-space, form the basis for describing natural entailment and for producing a more whole form of information that can be expected to carry important ecological information across science applications and to society. A generalized form of niche modeling can be specified as a robust means to describe such structure-function relationships, and thus to represent the complex entailments found in nature. The method of niche modeling must have certain general features for it to perform for this and other purposes, such as common distribution modeling. A parametric method is desired so that model parameters can be stored directly and documented, allowing them, as well as the limiting variables, to become the subject of modeling themselves. This builds into the architecture a natural way of representing feedbacks that are critical to capturing

complexity. Secondly, the parametric description of the niche should conform to ecological niche theory, so that distributions can be estimated not only on the basis of statistical associations, but also on theoretical grounds, allowing information from lab, field, and expert knowledge to be used. Conformality with ecological niche theory has another purpose, which is to afford experimental design and hypothesis testing on the actual response functions, thus learning more about the causal entailments. Outputs from such a process may be viewed as temporary results—hypotheses of a causal analysis in an interative framework. A method of *Modified Gaussian Niche Composition* (MGNC) is proposed here based on environmental limiting factors, an approach that lends itself to more general application for exploring the ecological basis for distributions, hypothesis testing, and for relating structure and function in an ecological informatics architecture. The MGNC method is to construct a niche hypervolume in environmental space according to response functions along the niche dimensions, then to isolate modes in each dimension and in the combined response. Isolation of the modes is theoretically justified on the basis of adaptation theory. It is necessary in this approach to make assumptions about how factors correlate, to be able to combine the axes unambiguously. By this method it is possible to specify a parameter to alter the way dimensions are composed, scaling between different types of distribution (physical to ecological). The resulting modal niche specifications, taken separately or combined with various interactive assumptions, can subsequently be used to create "suitability" landscapes and to map geographic distributions. More importantly they can exist in an information system to represent complex mutual relationships between the structural data and functional categories (which may be associated with models). By modifying the Gaussian equation, effects such as flattening (negative kurtosis), skewness, and covariance, can be represented. Three general tests of the method demonstrated its potential effectiveness and the validity of the assumptions. The overall architecture comprising structure and function representations and cross-referencing niche models could provide the \basis for new informatics that would be capable of supporting complex query, or driving models and simulations.

Introduction

There are many approaches to niche modeling. Here, I describe a niche modeling approach that has the desired properties for implementing a relationally complex architecture for eco-informatics. The aim of this approach is not solely to estimate a theoretical distribution, although that is one useful result; but rather to model the relationships that govern ecological distributions so they may be tested and refined as hypotheses of relational entailment. This in turn allows their use as integral components of informatics, defining the contextual relations of structures and functions. The approach is based on the theory of relational complexity described in Chapter Two that allow its application to ecological informatics (**Figure III-1).** The essence of this approach is a translation from a presumed relational organization of natural systems (shown as the background entailment circle in blue), to empirically accessible relationships between structure (S) and function (F) (shown as the foreground entailment circle in red). Structure and function are equated with the theoretical "encoding" and "decoding" relations of a natural system (a Rosen modeling relation), and are thus the means of translation between "the ontology" and "the epistemology" of a living system. This provides a strong foundation in systems-theory from which we can build a more natural and robust architecture for ecological informatics (with clear implications for theoretical ecology).

Structure and function can be determined as observed states and inferred potentials, which can be stored as data on states and models of function, each dependent on the other. Their mutual dependencies can be described in terms of two distinct types of entailment to recapture the underlying natural complexity that is characteristic of a modeling relation (and, theoretically, all natural living systems). In this way, informatics can be based on more natural 'building blocks' that do not force it into a strictly mechanistic description.



	Epistemology	Ontology
F	**function**	(decoding)
S	**structure**	(encoding)
NS	(selection)	**natural system**
FS	(specification)	**formal system**

Figure III-1: Translation from ontology to epistemology

In this approach, the fundamental unit of analysis for any living system is a modeling relation, which describes the entailment between components of a living system. System descriptions based on this relation can be constructed using relational mappings in category theory (Louie, 1985; Rosen, 1958b). The assumptions of this theory sharply contrast with the assumptions of mechanistic analysis, which decomposes nature into material objects and systems that are not self-entailed. This difference is important for informatics in that it requires equal attention to descriptions of system-specific functions—as the agents of change in living systems—in addition to observable states of a system (cells, organs, organisms, populations, taxonomic classes, communities, ecosystems, etc.).

There are two kinds of structure-function relationships required to properly represent the underlying complexity in nature according to this theory. These are: (1) the *'direct'* constraint or expression of an ecological function within its larger system context and (2) the *'indirect'* attraction and mutual selection of structures and functions as potentials that drive system development and behavior. An appropriately generalized niche model can be used to implement both kinds of relationships in the informatics.

This paper presents work in developing a generalized niche modeling method that can be used to model functional distributions; and that also has the desired properties for integration into complex informatics architecture, to provide the key relational elements described above.

Background

The ecological niche concept was introduced by Grinnell (Grinnell, 1917) and Elton (Elton, 1927), and later became defined by Hutchinson's "*n-dimensional niche*" concept (Hutchinson, 1953), and McArthur's quantification of "*resource axes*" (MacArthur, 1972). As adopted in ecology, the niche describes the complete relationship between an organism and its environment (Odum, 1953). Liebold points out that in practice the niche concept has been used to describe "*impact*" on the environment in addition to Hutchinson's concept that focused more on resource "*requirements*" (Liebold, 1995). This difference shows up in the distinction between habitat requirements and organism function (function performed). These ideas combine in the concept of "niche construction" (Odling-Smee, Laland, and Feldman, 2003) where '*what an organism does*' can be considered in assessing *'what it requires.'* Niche theory has also been used in social science, notable to assess the *"how differential ecological strategies attract participants"* (Eighmy and Jacobsen, 1980). We will see that these three interpretations of the niche are combined in the relational theory explored here; (1) as a constraint on the distribution of functional units according to their requirements (2) as a constraint on the expression of functions, and (3) as an attractive potential for niche occupation. A generalized approach to niche theory can thus provide the central method for relating structure and function.

While it is common to consider ecological response along resource axes and to quantify potential distributions in terms of appropriate environmental gradients is now a common method in spatial ecology (Austin, 2002); however, Heglund (quoting Austin and Meyers) stated that: "*failure to recognize the various shapes of response curves may result in inefficient or incorrect predictive models*" (Heglund, 2002). The niche concept has traditionally described how organisms (usually aggregated by species) are limited in some measure of their viability (abundance, biomass, density, etc.) within an ecosystem. Such limits are commonly described in terms of functional response along environmental dimensions that are considered most important for a given analysis.

This dimensional analysis is distinguished from generalized habitat classifications, which may not be specific to any given organism, and a wide range of other ecological mapping methods and philosophies, all of which could, in theory, be replaced by a general approach to niche analysis and modeling (Chapter Three).

Because of their fundamental theoretical importance, niche models can play a pivotal role in biodiversity and ecological informatics. Ecological questions by definition are about the relationship between organisms and ecosystems (environment + other organisms) and thus they require an ability to relate environmental and biological data.

In relational theory, the niche may be associated with a modeling relation in terms of the fit of a living component into a living system (Rosen, 1991b: pg. 120), which untraditionally takes a more expanded perspective on the elements of nature that are being related. Whereas in traditional niche theory we may imagine an organism, which is living, in an environment that can be treated more or less like a physical system (material "resource" constraints on the organism), a pure application of Rosen's terms would suggest it is really a relationship between two living or complex systems, each of which have both structural and functional aspects. We are unable, however, to consider structure and function together because our mode of analysis has separated them. We can retain the ontology, however, by remembering that the niche involves equally both a functional fit into a structural environment, and a structural fit into a functional environment: We must therefore consider reciprocal models comprising a more unified natural entailment. Perhaps it is now clear how this differs from a mechanistic analysis, where it is imagined that there is a one-way entailment between highly reduced concepts of structure and function.

It is important to remember that in relational theory structure and function are not the real objects of nature (natural systems are), but rather they correspond to information processes (encoding and decoding). An organism or ecosystem is therefore not to be considered a physical object or 'thing' any more than it is an unrealized functional potential; it is both. The question at hand, then, is how (or if) this kind of reference to nature can be stored and causally entailed in an information system to reflect its origins in nature. The appropriate information system will surely be unusual.

Taking care to generalize the traditional view, the niche model accounts for the theoretical constraint on a living system component (an organism or other functional component) by its environment (the ecosystem), and accordingly represents the variation and range of the component system's possible expression (and existence). A niche model can thus be used to generalize expected distributions across data gaps (a purely structural view), or to represent potential fields (a purely functional view). In addition to being a measurable result of ecological relationships, a species distribution is also a potential field consisting of all the functions the species may express. Likewise, combinations of organisms represent combinations of functions, or functional clusters. The niche model thus provides a way of composing and decomposing functions, and a way of composing and decomposing the potential structural realizations of functions (i.e., which organisms fill a function). This two-way entailment will be discussed later as part of an informatics design. Meanwhile, it is clear that the basic mathematical relationship of a niche model is the same for both uses (structure and function), so the first task is to explore how best to model a niche for general purposes. In this task there has been considerable progress.

Early Approaches

Early approaches to niche modeling in the US Fish and Wildlife Service centered on the development of "Habitat Suitability Indices" (HSIs). HSIs, however, were "*not research models*" but "*practical, operational planning models designed to assess impacts of change"* and "*a bridge between the fields of planning and science*" (Schamberger and O'Neil, 1986). Chalk, however, reported poor prediction results from HSIs due to unconsidered dynamics and scale issues (Chalk, 1986). More recent reviews (Scott et al., 2002) indicated dramatic improvements in the preceding two decades, although considerably more work was needed, particularly on issues of scale and dynamics (O'Connor, 2002).

Habitat Suitability Models (HSMs) were a more scientific approach succeeding HSI's. They were early niche models that were successfully applied where equilibrium assumptions held (Nielson, 1991; Rubec et al., 1999). Today's niche models can be considered further developments along these lines.

Our ability to successfully apply niche models to questions of distribution, suitability, productivity, viability, etc. has risen sharply in recent years, offering an important and fundamental tool for ecological informatics. A common application of ecological niche modeling is to infer distribution of organisms by correlating their known occurrences with variation in environmental parameters, and thus to produce maps of potential distribution (as estimates of suitability or probability of occurrence). Niche models have already been extensively applied to a variety of questions regarding past, present and future distributions of organisms (Peterson, 2003; Peterson, 2006; Roura-Pascual et al., 2006). They have also been used to show areas where populations of species are likely to occur, helping to target sampling efforts and providing a more robust assessment of biodiversity (Guisan and Zimmermann, 2000).

The primacy of the organismic niche concept has been emphasized by many authors (Scott et al., 2002). The concerns of Wiens' and others' regarding dynamics, heterogeneity, and scale (Wiens, 2002), can also be considered to the extent that they can be represented either in (a) innovative control variables, such as a niche variable defined on metapopulation matrix requirements (Gehring and Swihart, 2003; Stacey and Taper, 1992), (b) distinguishing niche components for corridor, source and sink habitats (Rosenberg, Noon, and Meslow, 1997; Mabry and Barrett, 2002), or (c) iterative succession of models simulating dynamic changes in habitat controls. It is generally recognized that Geographic Information Systems have become a primary tool in such work, but that they should be effectively integrated or linked with models (Goodchild, Parks, and Steyaert, 1993; Goodchild, Steyaert, and Parks, 1996).

To implement niche modeling in an operational setting, it is important to ensure selection of appropriate controlling variables and the technique for niche construction. These semantics of model construction are of prime importance with regard to selection of statistical and mathematical techniques, as emphasized in two major reviews of distribution modeling. (Scott et al., 2002; Verner, Morrison, and Ralph, 1986). These needs may be envisioned as a set of choices that may be made available in a software interface, with suitable documentation and superimposed information tracking to ensure proper use of the model.

The traditional HSI method (Schamberger and O'Neil, 1986) can be extended considerably to deal with a range of different cases, and can serve as the basis for a general method for predicting organism and higher taxa or eco-unit distribution limits. Prediction of actual, realized niches, however, is a matter of complex functional relationships, dynamics, and history. The purpose of a generalized niche modeling technique is to delimit the boundaries of a potential distribution, which then could be employed in predicting actual distributions. Complex (unpredictable) dynamics can be simulated by interacting ecological systems, functions, and niche distributions iteratively.

Most niche modeling techniques today are grounded in statistical or genetic recombination theory, which are forms of pattern matching. Each technique necessarily makes assumptions about the mathematical form of the ecological distribution in terms of an underlying statistical model. The decision of which kind of distribution is appropriate is a proper ecological question for which ecological theory remains weak. With few exceptions, niche models have been instrumental applications of mathematical patterns with little if any claim to ecological theory.

Theoretical ecology has always had problems (Simberloff, 1981), but perhaps the most extreme recent challenge was Gaston and Chown's concept of "niche neutrality" (Gaston and Chown, 2005), which was interpreted by many as challenging the fundamental niche concept itself. Their actual thesis was that in specific circumstances species occurrences may be random across a region of fairly uniform suitability. The idea was developed for explaining seemingly random (rather than niche-segregated) mixing of species within a very stable and climatically uniform tropical forest. However, their observations are fully accounted for in terms of uniform overlapping niches and corresponding distribution where spatial segregation itself dominates. The environmental niche does not theoretically exclude proximity as a factor, nor does it pinpoint locations of organisms or species. The niche describes adaptive regions in environmental space that may be sharp or broad, where conditions are suitable for the organism. Those conditions may be distributed in any manner geographically, with various forms of spatial autocorrelation. The translation of a niche specification into geography may therefore produce relatively homogenous regions, patches, or entirely stochastic patterns depending on the distribution of factors. Neutrality theory mostly challenged the idea that resource partitioning must be accomplished by niche segregation, which itself is a misunderstanding of the niche. It is well known, for example from studies of Serengeti ungulates (Sinclair and Norton-Griffiths, 1995), that when resources are productive and uniform, animals can co-exist by segregating resource use by time of day. The neutral-niche random spacing in tropical forests is a similar solution to the problems of a relatively uniform, shared niche. These cases where stochastic distribution arises from niche overlap in which adaptation for such distribution is possible, and can thus provide the theoretically necessary segregation. It is important to distinguish an ecological function itself (what the organism does or needs) from its general distribution, which is what the niche describes, and within which geographic interaction can dominate the pattern.

The ecological niche still holds a central position in ecology, similar to that of evolution in biology. Strictly speaking, the niche is the expression of the concept of adaptation: Given that organisms adapt, adaptive phenomena can be expressed in terms of a niche.

Niche Model Design

There are a number of niche modeling techniques that have been introduced in recent years. These include parametric and non-parametric approaches, and a wide range of assumptions about how to combine functional responses along the separate niche dimensions in a multivariate environmental space. There is no accepted theory for which method is right, so these exercises are primarily instrumental applications that must be tested on a case by case basis. Once a niche hypervolume has been defined, however, the theory for mapping it to geography (for example in a Geographic Information System) is clear, and involves an unambiguous application of spatial gradient data for each variable. The theoretical difficulties with niche modeling lie mainly in defining the hypervolume, and include: (a) determining the limiting variables to use for dimensioning the niche space, (2) describing the functional response in each dimension in such a way that they can be combined, and (3) determining the appropriate method for combining the functional responses. Because of these theoretical unknowns, there are many possible techniques that can be applied.

A recent modeling environment, OpenModeller (Sutton, de Giovanni, and de Siqueira, 2007), includes a variety of optional techniques, among them: BIOCLIM (Nix, 1986), BIOCLIM Distance (removed), Climate Space Model - Broken-Stick, Distance to Average (deprecated), Environmental Distance (Carpenter, Gillison, and Winter, 1993), Genetic Algorithm for Rule-set Production (GARP) (Stockwell and D. Peters, 1999), GARP with Best Subsets Procedure (Anderson, Lew, and Peterson, 2003), Minimum Distance (deprecated), Support Vector Machines. Aside from those in OpenModeller, other niche modeling systems include: Biomapper (Hirzel et al., 2002), WhyWhere (Stockwell, 2006), KGS Mapper,[21] and Hyperniche (McCune, 2006). In addition, a number of analytically-oriented Geographic Information System packages contain similar functions, for example Multi-Criteria Analysis (Eastman and Jiang, 1996) and other tools in Idrisi (Eastman, 2006), and various functions in DIVA-GIS (Hijmans et al., 2003). Each of these methods has advantages and disadvantages. The literature on use of various niche modeling techniques in many fields of landscape ecology, agriculture, forestry, and even the social sciences has grown rapidly in the last five years. However there is still poor understanding of the ecological assumptions embedded in these techniques, as was the case with their predecessors (Huston, 2002).

An extensive comparison of techniques has been carried out (Elith et al., 2006), yielding the following results (Pearson's 'r' correlation is cited to allow comparison with the MGNC model results presented later):

1. The various model performance measures were highly correlated, and thus essentially equivalent in their diagnostic power.
2. There was considerable variation in model performance, showing improvement in the more recent techniques over the older ones.

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[21] http://drysdale.kgs.ku.edu/website/Specimen_Mapper

3. Non-parametric methods did a better job of matching data but raised questions of “overfitting;” that is, calculating too exact a fit to a limited data distribution. Parametric methods, on the other hand, may tend to over-generalize, mapping a mathematical function rather than empirical reality.
4. Models that could incorporate community-unit proxies (using environmentally or ecologically related species as predictors) performed better.
5. Models that employed pseudo-absence data (assumptions, in the absence of data, about where there should be no occurrences) tended to perform better.
6. The Generalized Dissimilarity Model (GDM) using community data had the best performance on separate trials ($r \approx .3$). The Boosted Decision Tree (BRT) model gave the best average performance ($r \approx .21$), followed closely by others clustering around $r \approx .2$.
7. There was much greater variation in performance by location and species ($\Delta r \approx .25$) than between models ($\Delta r \approx .16$).
8. Average model performance spread evenly between $r \approx .14$ and $r \approx .2$; and the difference between the best and worst model performances in separate trials was fairly constant at $\Delta r \approx .1$, with different models taking the lead in different trials.

These results support the assumptions and rationale employed here in a number of ways. An obvious conclusion is that considerable room for improvement exists in niche modeling, particularly in how niche factors are selected and represented. It appears that factor selection or other unknown determinants of the distribution (such as dynamics) are a much greater problem than model design. Niche factors (limiting variables) are, in general, poorly known. Variable performance can thus result from scale-dependent landscape heterogeneity, unknown physiological or ecological relationships, or differences in system dynamics that disrupt the equilibrium that a static niche model attempts to describe. This result suggests that niche modeling should be more about discovering these factors than obtaining a precise fit to limited data, and that a proper implementation of niche models might be as dynamic potentials rather than static descriptors. This supports an iterative approach to model definition and application so that the model can learn and converge on stable conditions (based on experimental inputs), or so that it can follow dynamics (based on functional expression), or both. The greater generality of a parametric approach could be an advantage if the parameters correspond to ecological theory because their dynamics can then be represented mathematically, and other elements of theory (e.g., dynamics) can then be added to explain differences between observed and actual distributions.

Greater emphasis on ecological theory also seems appropriate because most species occurrence data are poorly sampled, have considerable biases and very incomplete coverage, suggesting that variation in how statistical assumptions treat poor data dominate the test results. Better theory would allow better application in data poor situations, and use of other forms of knowledge besides statistical correlations, such as data on functional response from laboratory studies and even indigenous knowledge, translated into the appropriate parameters. The generally poor performance and lack of a clear “winner” in these tests suggest that none of the models stumbled upon a dramatically new understanding of niche relationships.

There was clear benefit in the Elith study from applying niche models to community groupings, again, a theoretical component. This suggests that generalizing niche modeling to a theory of functional decompositions and clusters (Christian et al., 2005), as proposed here, is an appropriate direction for research. A general approach could be applied to any functional distribution of which organisms are an entailed component, including different taxonomic groups and ecosystem services. This has implications for theoretical ecology. Whitaker's interpretation of the classic Gleason-Clements debate (Perry, 2002), began a move from "community unit" to "individualistic" distribution concepts. (Collins, Glenn, and Roberts, 1993) offered a logical compromise in that debate, in terms of a "*hierarchical continuum*" between individual niche distributions and more aggregate units with which individuals and/or species may have important relationships, thus integrating both sides of the debate. Niche decomposition conforms very well with Collin's proposal and relational theory. It assumes that each niche describes a functional component of a system, and that functions can be composed and decomposed into various holarchical entities.

Another area where better ecological theory may help is in dealing with presence only data (which is characteristic of species occurrence data, for example widely available museum data). The Elith et al. study found that incorporating assumptions about absence improved model performance. However, their use of random sampling to represent absence is case, scale, and area dependent. A better assumption is needed or else it must be made dependent on these factors. Theoretical consideration of clumping (as a function of ecological distance) and spatial heterogeneity (as a function of scale) could improve estimation of absence. A parametric description of the niche hypervolume could, for example, include a measure of ecological distance beyond which absence is more likely.

Finally, all of these conclusions support the proposal here, that niche modeling should be an integral part of a scientific informatics enterprise, in which a model's theoretical validity becomes a central part of any investigation. Niche models should be implemented as hypotheses about ecologically controlled distribution. By incorporating them into an applied informatics architecture, both their use and their iterative testing can be systematized.

Based on the above analysis, the following design goals for the niche model can be stated:

- General applicability to system-dependent functions.
- Parametric association with ecological theory.
- Ability to represent functional compositions and decompositions.
- Scale independent assumptions (scale being a function of the database).
- Theoretical estimation of absence.
- Architectural embedding in informatics to allow relational links and iterative development.

The goal of this approach is to map functional suitability for a given 'component' of a living system. This is done according to functional response in n-dimensions of an "ecological niche space." This can be applied to taxonomic groups, individuals, ecological units, and arbitrary stratifications for sampling or query purposes. "Ecological" in this usage means the relationship existing between a living system and its larger environment. This definition includes both anthropogenic components of the system of interest and anthropogenic determinants contributing to the niche definition. The term “socio-ecological” (Kineman and Parks, 1997) has also been used to emphasize an integrated approach that can handle multiple types of limiting variables.

Methods

I present a general parametric method, the “Modified Gaussian Niche Composition” (MGNC) model. This technique uses multi-dimensional response functions to specify a potential niche hypervolume. The response curves of this model are based on a modified Gaussian (negative power exponential) form with parameters that can be estimated from data or supplied from other sources. The model produces a “suitability” distribution in environmental space that can be mapped to geographic space using gradient data layers for each dimension. The approach decomposes the niche into resource axes that represent functional response to limiting conditions ((Pykh and Malkina-Pykh, 2000). The parameters of each response function are then combined to produce a hypervolume in environmental space. The magnitude of the hypervolume (response variable) is calibrated as a “suitability” ranging from 0 to 1 (and thus not normalized to produce a probability density function). That mathematical function can then be applied to the appropriate datasets, representing the response axes, to map the distribution geographically.

While it is true that non-parametric methods can more accurately describe an actual data distribution in multiple dimensions, this may not be the best choice. As discussed above, it is rare to have sufficient data to completely describe a niche in a theory-neutral manner. Additionally, non-parametric clustering algorithms require considerable computational power (Hoffman and Hargrove, 1999), limiting their use in a more entailed system architecture. But the most important reason for using a parametric decomposition technique is that the basic elements of the model can be individually evaluated with regard to their ecological meaning, and modified according to empirical and expert knowledge. The model thus becomes a research tool about ecological relationships.

The Gaussian form is a natural choice for ecologists because of its fundamental interpretation in niche theory as a basic modal response. The meaning of its parameters are well-known as the normal distribution, however it is also known that most real-world distributions cannot be resolved into this ideal. Modifications can be made, however, for kurtosis (flatness), skewness, and covariance, producing a general form that can be composed with others or decomposed into sub-models, where theory or data allow. This allows for scaling of the model technique from the simplest case of a relatively normal unimodal distribution to more complicated hypervolumes with multiple and variously skewed and kurtotic shapes.

The Modified Gaussian Niche Composition (MGNC) Model [22]

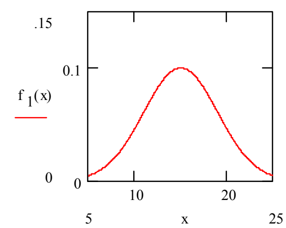
The basic form of the Gaussian curve is the negative exponential of a random variable, x. This is the basis for the Gaussian "normal" distribution specified by parameters for mean and standard deviation, expressing the independent variable as a

[22] Equations were written and all model results produced in *Mathcad 2001i and 12,* from Mathsoft, Inc., http://www.mathsoft.com/. Geographic models were produced in Idrisi Kilamonjaro, from Clark Labs, http://www.clarklabs.org/

distance from a central location, μ, scaled by the standard deviation, σ. This establishes the standard normal (**Equation III-1**, where μ is the mean and σ^2 is the variance), as shown in **Figure III-2**:

Eq. III-1 $$f(x) \equiv \exp\left[\frac{-(x-\mu)}{\sigma^2}\right]$$

In statistics this basic Gaussian distribution is normalized so that the integral of the function is always 1, that is, to scale it as a probability density function (*pdf)* where the probabilities (area under the curve between any two values of x) sum to 1 for the whole distribution. It is conventional to define a probability of 1 as certainty, so this means the curve describes, theoretically, all possible occurrences.



$\sigma \equiv 2 \quad \mu \equiv 15$

Figure III-2: Gaussian distribution

Because the goal here is to produce a measure of *suitability* not probability, it makes more sense to use the un-normalized distribution, and to define suitability as the value of the function itself, which has a maximum value of 1. If necessary for a given kind of study, the function can be normalized later to represent probabilities. The goal here is to define a function that represents the response of an organism to conditions in terms of "suitabilities" ranging from 0 to 1, where 1 indicates a region of the niche space that is considered 100% suitable for the given taxon, group, or individual function. 0 may be defined as not suitable, but to deal more effectively with absence data and known instances of unsuitability, it may be better to define -1 as completely unsuitable. Negative distributions can be very useful to represent a negative potential when combined with other distributions, thus leaving 0 to be interpreted as neutral or unknown (providing a means for handling absence of data as recommended by Elith et al., discussed above). Negative distributions can be used, for example, to represent competitive exclusion between species. These options can be included as choices in the implementation of the model.

At this point a curve has been specified based on the un-normalized Gaussian distribution, employing the first and second central moments, which are the mean (the expected value of the first moment of a distribution, $(x-\mu)$) and Variance (the second moment, or expected value of $(x-\mu)^2$), to specify the function. These conform well to both statistical theory and ecological theory because so far the function only specifies a central tendency, which is theoretically valid in both cases. Any variable that represents a factor that could influence survival or viability of the organism will have an adaptive range, by definition, above which and below which conditions are less suitable for the organism (or its performance of a function).

We can specify a variable in such a way that the response function is not modal, but usually some thought will reveal a more appropriate specification that is restrictive on both sides of a mode. For example, we could say availability of a proper mixture of air is a niche variable. Then it is clear that too little affects viability or performance whereas there is no such thing as too much availability, as such. But if instead we specify partial and/or total pressure, it is clear, as SCUBA divers know, that there is definitely a range, either side of which conditions are sub-optimal. Availability of water is a typical resource axis for wildlife habitat studies, and again, in a habitat analysis, one might simply confirm that a minimum threshold has been reached. Is it then possible to have too much water availability? Certainly if we consider where all that water is and what other effect it has on the activity of the organism, there can be. So, for niche modeling it would be better to think about how to specify this resource with regard to its independent nature and total effect. For example, 'distance to water' has both a minimum and maximum optimal value, on the one hand including all consequences of being near the water (including increased predation) and all the consequences of being far (greater effort to obtain water). 'Amount of rainfall' has more effects, positive and negative, than 'availability of drinking water,' which is partly dependent on some aspect of the organism (drinking abilities). In other words, one should define niche variables, whenever possible, in a way that represents an independent property of the environment that affects the organic, adaptive function.

It is well-known that normal Gaussian distributions are ideals that rarely fit real data, perhaps due to both theoretical and practical reasons. One must therefore be able to modify the ideal form to model the response, and if this is done in an ecologically meaningful way, one can test hypotheses about the parameters that define response functions, and also one can test hypotheses about components of a distribution that may be an aggregate of phenomena (i.e., the principle of composability). It is thus more useful to modify a theoretical distribution than to move to entirely instrumental methods for just "fitting the data" (i.e., correlations alone). There are two modifications of the Gaussian that might be particularly useful for establishing a general method. These are commonly measured (in statistics) as "skewness" (the third standardized moment, which is the expected value of $((x-\mu)/\sigma)^3$), and "kurtosis" (the fourth normalized moment, which is the expected value of

$((x-\mu)/\sigma)^4$, or sometimes it is calculated as the fourth normalized cumulant and usually 3 is subtracted so that kurtosis = 0 for a normal distribution). The effects measured by skewness and kurtosis can be produced by a variety of modifications of the Gaussian. The purpose here is to employ simple methods for applying these modifications to produce a continuous function representing ecological suitability, while retaining the ability to estimate the parameters of that function from data. For this purpose, I define asymmetry, which may be estimated by skewness, and flatness, which may be estimated by negative kurtosis with appropriate transformations.

Asymmetry

It is possible to produce asymmetry in a model by a variety of means. It may be difficult, however, to match a given method of producing skewness to its statistical calculation or to ecological theory because it can result from many different causes, including physiological adaptation, compositional differences in populations sampled, or how a variable is defined for a given measurement and thus how it scales with respect to organism-based response (for example, by a log or power function). If, for example, skewness is due to a mathematical characteristic of the chosen variable, it may be best handled by an appropriate scaling or transformation of the axis, however, that requires prior knowledge of the function and it would also preclude combining multiple modes and models. Since a goal here is to allow functional composition and decomposition, some other approach is needed.

An approach has been used for un-mixing spectral signatures into separate Gaussian modes, using a polynomial modification of the Gaussian (Sunshine and Pieters, 1990; Sunshine et al., 1999; Kanner, Mustard, and Gendrin, 2007; Vivo-

Truyols et al., 2005). The first term of the polynomial provides a crude form of skewness (**Figure III-3**). However, this method has the undesirable property of increasing in value at distance from the mode (see left tail), especially for high asymmetry values. Another method produces a “skew normal distribution,” by multiplying the Gaussian Normal distribution by its cumulative distribution, offset by a scale factor (Azzalini and Capitanio, 1999). This distribution has desirable statistical properties, but it may be difficult to estimate the skew factor from data, or associate it with ecological meaning.

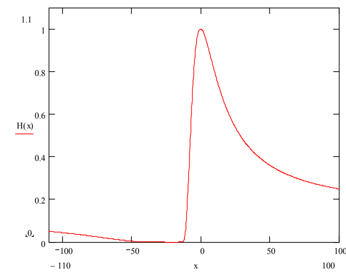


Figure III-3: Polynomial Modification

Asymmetry can more easily be incorporated into the model, estimated parametrically from samples of occurrence (and/or absence), and interpreted (or applied) theoretically, by using asymmetric parameters for the deviation of x (σ_{xa}, σ_{xb}) for half-normals on each side of the mode (**Equation III-2** and **Figure III-4**). This approach has the advantage of being referenced to a fixed position of the mode, which is more important in niche theory than an overall mean. The mode thus corresponds with the theoretical means of two underlying symmetric Gaussian forms with different parameters, and the final distribution corresponds with the maximum of the two

Eq. III-2

$$X(x) \equiv \begin{cases} \dfrac{x - \mu_x}{\sigma_{xa}} & \text{if } x - \mu_x < 0 \\ \dfrac{x - \mu_x}{\sigma_{xb}} & \text{otherwise} \end{cases}$$

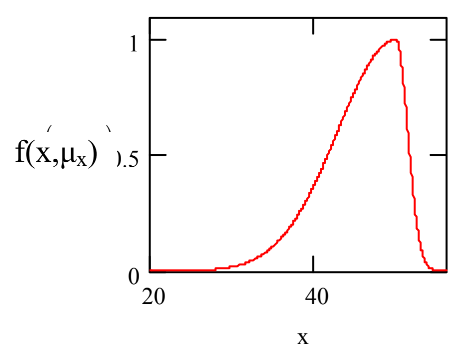


Figure III-4: Asymmetric deviation

functions on one side and the minimum on the other. This method is open to theoretical interpretation, for example, two distinct physiological processes that limit the function differently at high and low values, much as in the examples above where, for example water stress may the limiting factor at low values while predation or locomotion may be the limiting factor at high values. We thus have the advantage of decomposing these separate functions. The technique is flexible, easy to calculate, and gives the same desired effect as the Skew Normal. The mode of the distribution can be quickly determined visually[23] or by a number of mode estimators (Hedges and Shah, 2003; Bickel and Frühwirth, 2006; Bickel, 2003; Bickel, 2002).

Flatness

It is widely known that ecological distributions can be “flat,” with sharp sides, as in the extreme case of niche neutrality discussed above, which is a uniform distribution across a range. Uniform distributions are often assumed in GIS analysis, when polygon data are used or when a species distribution or ecological definition is calculated by the crude method of range overlay. Obviously there are cases where distributions are indeed broad and flat enough to be approximated by such methods, and cases where suitability is much sharper, so a method for scaling between these cases would be appropriate for ecology. Ecological distributions do not tend to tail out to infinity, nor is there generally a sharp optimum value, but more often a fairly uniform response over some region of suitability within which other dynamics take over, as in the examples given earlier, and then a sharp decay to zero. The un-modified Gaussian provides a basic modal shape, but its gradual tailing out to

[23] With user interaction there is nothing wrong with a visual estimation of the mode, given the roughness of most data and the fact that the technique is designed to be used iteratively.

infinity, which is true for statistical distributions, is not necessarily good for modeling ecological ones, which typically have strong self-limiting characteristics.

There is a useful modification of the Gaussian that flattens the peak and truncates the tails by changing the power of the negative exponential (**Equation III-3** and **Figure III-5**).

Eq. III-3

$$\phi(X,k) \equiv e^{-\frac{1}{2}\left(|X|\right)^{k}}$$

$$X(x) \equiv \frac{x-\mu}{\sigma}$$

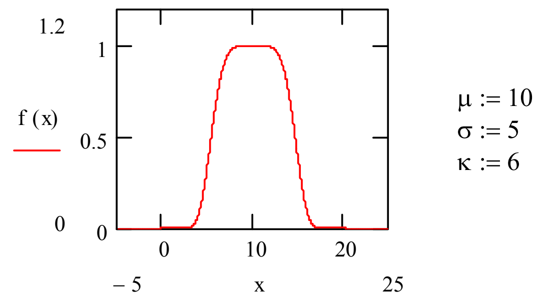


Figure III-5: Flatness

These parameters of the response curve (mode, deviation, asymmetry, and flattening) may be estimated from data using the corresponding statistical measures, or they may be supplied from other knowledge. The shape of the response curve can be controlled considerably with only these four parameters. *k* can be related to standard statistical calculations of kurtosis for purposes of parameterizing from data.[24]

Combining Niche Dimensions to Produce the Hypervolume

The next problem is how to combine the multiple niche dimensions and which variables to choose for the model. The specific type of combination to be used depends on one's purpose and the type of variable used to construct the model (Huston, 2002). For the MGNC approach, a method is needed that is:

[24] I have not worked out the exact relation, but approximate it as *kurtosis* = 2.8 + 2.4/k

1. easily scaled to n-dimensions,
2. based on observational variables representing ‘true’ ecological limits,
3. robust to correlated and compound variables,
4. related to ecological theory, allowing ecological hypothesis testing and error analysis,
5. capable of providing direct and indirect relational entailments discussed earlier.
6. easily applied iteratively, to converge on more correct relations and factors, via experiment.

Observational variables may typically be correlated or compounded (Trodd, 1996), requiring care in their selection for each type of model to avoid conflating different types of data, for example indicators of presence (which is the dependent variable being estimated by the niche model), probabilities of occurrence, and true ecological niche factors.

Models dimensioned on indicators of presence are not true niche models, as they do not specify the constraining relationship between the organism (or function) and its environment. Generally speaking, indicators are either additive, or if expressed as probabilities, multiplicative. Habitat Suitability Index (HSI) models are of this type, typically involving checklists of presence/absence or habitat and resource factors. Many of these are ecological factors, but in most HSI’s the modal response function is not estimated. The relative importance of various indicators also may not be evaluated or testable, or part of the approach.

A probability of occurrence model is somewhat more robust than an HSI, because expression of indicators as probabilities allows multiplicative combination, i.e., each variable conditioning the effect of the others. However, these are conditional probabilities, dependent on the conditions governing that response being present. For example, availability of blueberries in summer may be a good indicator of the likelihood of finding bears, but it presumes that there is no other food supply nearby that the bears will prefer. These conditional factors are rarely evaluated. Many cases combine environmental variables and habit factors and indicators together into a statistical technique that treats them all as equal and uncertain indicators. The probabilities in that case include ecological uncertainties and uncertainties in knowledge, without much attempt to distinguish them by theoretical considerations or experiment. Factor analysis can reveal which factors correlate best with response on a case-specific basis, but the result is not a general model if too much ecology has been left out of the analysis, looking only at rank correlations. Again, the habit of doing this comes from physical science, where many relationships are better known and it is thus more likely that reasonable factors will be selected and correlations will suggest a causal relationship. For instance, one would not include data on the location of outhouses in a physical model of where meteorites might be found, even though a positive correlation might exist simply by chance or because of sampling bias. However, in ecology almost anything can have a relationship and in fact the location of outhouses is a good indicator of certain human cultures in South America that tend to use a specific variety of corn, so a causal relationship does exist through a proxy for a human limiting factor on dispersal and cultivation of corn.

Differences between physical and ecological limitations should also be considered in selecting niche constraints, as they imply different kinds of response surface. Physical constraints act, in essence, as infinitely sharp gradients in some adaptive factor(s), resulting in an absolute barrier. Because the barrier is more obvious than the ecological factor, the available data would describe the physical features, such as shore lines, roads, or buildings. One would then need to process the data to represent the implicit ecological factor for niche modeling, or use it as-is in a physical instance of the model (described below). The niche dimensions should be combined differently in these cases. Where this distinction is hard to make (as for example a shoreline, which represents a physical barrier in some cases and an ecological zone in others), it is helpful to be able to model intermediate cases. For a niche model of oak trees we might treat the shoreline as a physical barrier, but for the niche of an amphibian we would be obligated to represent it in terms of ecological factors. As another example, a building obviously limits the viability of trees for which the area might otherwise be suitable. But the building is not an ecological factor as such. If the building presence were translated into its effect on all the physiological factors limiting tree growth and added to all the appropriate data layers, the model would remain ecological. But if data on the location of buildings are used directly, it is simply a geographic filter having no ecological relationship to other niche factors. In other words, one does not get a higher suitability for trees in buildings if other factors in the model are ideal, as one might for an ecological condition, such as water stress. This alters the theoretical shape of the hypervolume, as discussed below. If, on the other hand, the laborious translation to ecological factors is done, one could indeed predict which buildings may have trees—in a foyer or office space or for other decorative purposes—if all the ecological and social conditions for that are mapped. This suggests the power of true functional niche modeling, but also the limits of available data.

It is common to use proxy data in many instances, such as polygon data on habitat types, to generate the desired data layer in a GIS, such as gradients of substrate roughness based on habitat type, and then smoothed to prove approximate gradients (as good as the original data allow). This, of course, weakens the model but it is unavoidable. The approach for niche modeling should be to document the validity of the technique so that the effect of error in that dimension can be assessed later, or tested via hypotheses about its effect on the final distribution. Given the weakness of most models, and different sensitivity to each factor, it could be that costly improvements in one approximated data layer will make little difference in the result. It can be more important to iteratively test the whole model, and thereby determine which factors actually need improvement. In discussing proxies and occurrence models, it is worth noting that these are still useful in niche modeling as a surrogate for more direct field sampling, or for testing a true niche model, as in the example below where pollen counts were used to indicate picea abundance.

Given the importance of understanding how a variable limits or indicates a distribution and what is or is not a proxy or physical vs. ecological constraint, the model options can be divided into three cases requiring different techniques. Intermediate cases can be useful simply to strike a balance between unknowns in the variables being used. These cases are:

1. Indication or probability of occurrence.
2. Physical constraint
3. Ecological constraint (Niche)

Case I: Indicators of Presence

Most indicators of presence are additive and therefore must be carefully de-conflated and weighted relative to each other. If converted to probability gradients over the entire study area, they can be multiplicative, which eliminates some of the need to de-conflate correlated or combined variables (which is accomplished in the final mapping to geography). Additive models based on indicators of presence must therefore convert observations into orthogonal vectors ("eigenvariables") in order to avoid biasing the result toward one kind of indicator that may be correlated across multiple proxies. An assumption in this type of model is that indicators have either been made roughly equal in their diagnostic power, or they are weighted accordingly. When variables are correlated or compounded, it is the same as increasing the weighting of the correlated factor. For example, if both elevation and temperature are used as a predictor, the lapse rate with altitude is represented twice. If the variables are defined as indicators, conflation will result in over-emphasis of one uncertain factor vs. another.

Data on variables that are indicators of biological presence do not specify niche dimensions. They are direct estimates of the response variable (functional presence). Indicators of presence should not be used in the niche dimensioning itself, although, the distinction between an indicator and a proxy for some limiting variable can at times be hard to maintain. Generally, indicators are additive whereas limiting variables are mutually exclusive. Including this option in the overall suite of choices, even though it requires a different technique, helps ensure that it is kept as a distinct case, and may provide a useful tool for validating niche models. This kind of distribution is basically a weighted, additive habitat suitability index (HSI), which is typically produced by simple addition of terms (**Equation III-4**, where the parameter *p* determines relative emphasis on the stronger indicators as $p \rightarrow 0$.

Eq. III-4 $HSI = \left(\sum a_i S_i^{\frac{1}{P}} \right)^P$ which is the weighted sum of separate indicators, Si.

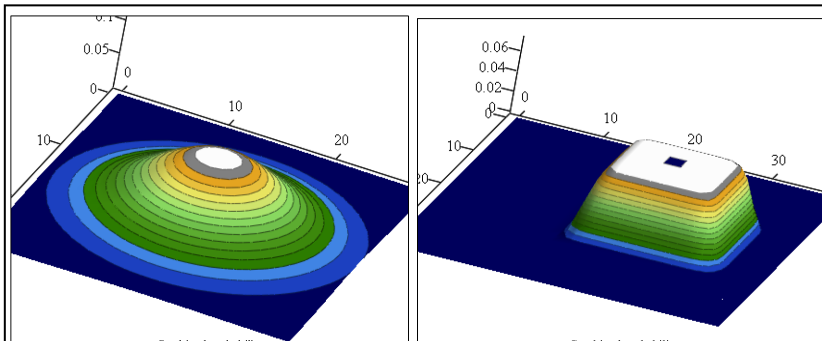
This is a logical OR condition, where any of the indicators of presence are sufficient to identify the corresponding location on a map as suitable due to presence of at least one of multiple indicators. The shape of the distribution function for each indicator and its corresponding weight can be determined by the investigator, typically from a statistical analysis of data for each indicator variable and its association with known locations of the entity being mapped. Many methods of estimating the response curve are available. If indicators are meant to be exclusive, a logical AND condition, then they must be multiplied, as in Case II below, or intersected.

Case II: Physical Limits, Acting Independently

Each variable in this kind of model acts as a limiting factor on the target distribution. It applies to physical limits or exclusive indicators. For example, if two physical niche variables are space and substrate, values of either one lying outside its suitability range would mean a zero total suitability. The result is a map where both conditions are met simultaneously. Variables of this type cannot be added (as with indicators), and so cannot be included in a Case I model. The traditional HSM method (Rubec et al., 1999) is often employed with this kind of variable to develop a multi-criteria index of habitat suitability. In this method the response axes are simply multiplied to produce a composite suitability value, the HSI. This is the geometric mean, as indicated in **Equation III-5** (for n-dimensions).

Eq. III-5 $$HSI = \left(\prod_{i=1}^{n} S_i \right)^{1/n}$$

This kind of model is easiest to interpret for S_i corresponding to an unmodified Gaussian normal distribution. When axes are combined, such distributions produce a symmetric, multi-dimensional Gaussian form as shown (**Figure III-6**, left). A great deal of criticism has been made of normal assumptions in ecological models (Scott et al., 2002), which were popular in theory for a time because of their simplicity and ease of calculation. Also, the theory of the Normal distribution is well established for statistics and probability. However, ecological distributions are rarely Normal. If some flattening of the Normal is introduced (say by the method described earlier), approaching a semi-uniform distribution, we see that the geometric mean of the axes produces considerable isotropy along the chosen axes. This “square cake” model (**Figure III-6**, right) is appropriate for discrete physical



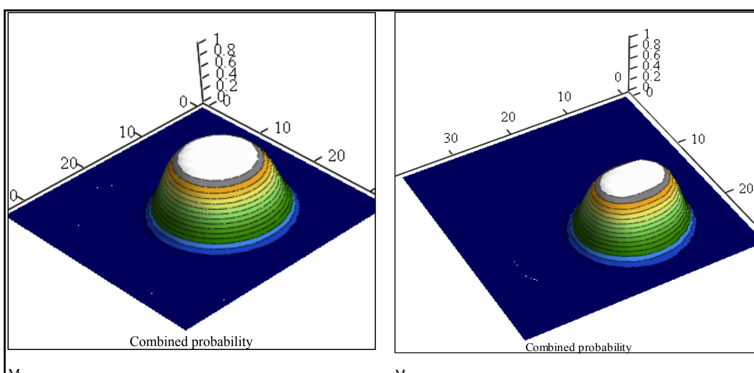
Geometric mean of Normal M Geometric mean with kurtosis

Figure III-6: Geometric Mean

limits acting independently. The inherently non-ecological nature of this kind of model is apparent in the fact that the niche breadth increases for linear combinations of the axes, an artifact of the model that has no basis in the ecology.

Case III: Ecological Limit Variables ("Law of the Minimum")

There is more reason to assume that in ecological niche hypervolumes the "ecological distance" would be anisotropic with respect to any preferred dimension, since an adaptive living function responds to the environment as a whole. Another way to think of the ecological case is to consider the combined effect from multiple "stressors," which mathematically is equivalent to positive and negative correlation at the same time. This eliminates the corners and rounds the distribution, as seen in **Figure III-7**. As an example, one may imagine a long walk in varying climates. There is an optimal amount of water for the trip. Too little and one will suffer from thirst, too much and one will over-exert from the weight. There is an optimal range of temperature tolerance. However, one can tolerate the highest and lowest temperatures only with the optimal amount of water. Similarly one can tolerate the highest and lowest amounts of water only at the optimal temperature. This synergistic effect rounds the niche shape. The organism responds as a whole to combined stress



Combining Equal Axes   Combining Unequal Axes

Figure III-7: Platykurtotic Niche Hypervolumes that is not evident in the separate axes. This implicit wholeness is part of the phenomena of the whole exhibiting properties that cannot be predicted from the parts (the separate dimensional response curves).

This case represents the ecological law of the minimum, or law of limiting resources. Modifications for skewness, flatness, and modal interaction all apply. I refer to this as the "round cake" model (as opposed to the "square cake" model, above). It is produced by calculating the parameters of a modified Gaussian function on the ecological "distance vector" (r) as shown in the composite **Equation III-6**, for any function, where k = flattening, σ = standard deviation; μ = mean/mode (using the approach of half-normals described above if skewness is added). A covariance matrix may also be applied as a function of the product of any two axes in r.

This model assumes adaptive dependence of all niche dimensions, and therefore no "squaring" along the axes. That assumes that the distribution in question responds to the whole of the niche, not to each control variable individually. This seems appropriate for functional responses, which are characteristic of adaptive, living (energy dissipative) systems, because their

$$\boxed{\phi(r,k) \equiv e^{-\frac{1}{2}\cdot(|r|)^{k}}} \qquad X(x) \equiv \frac{x-\mu_x}{\sigma_x} \qquad Y(y) \equiv \frac{y-\mu_y}{\sigma_y}$$

$$r(x,y) \equiv \sqrt{(|X(x)|)^{2q+(k_x)\cdot(1-q)} + (|Y(y)|)^{2q+(k_y)\cdot(1-q)}}$$

$$k(x,y) \equiv \left[2.001 + q\cdot\left[\frac{(|X(x)|)^2 + (|Y(y)|)^2}{\frac{(|X(x)|)^2}{k_x^{\,2}} + \frac{(|Y(y)|)^2}{k_y^{\,2}}}\right]^{\frac{1}{2}} - 2\cdot q\right]$$

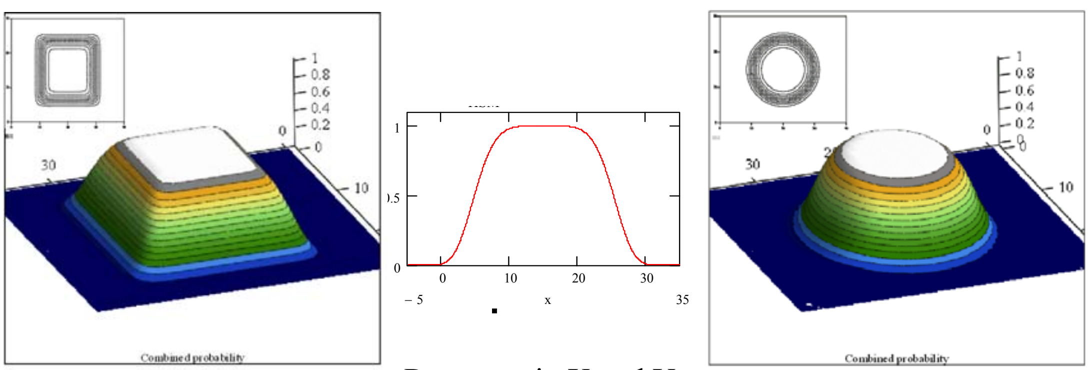
Eq. III-6: Generalized Niche model

viability depends on a dynamic balance of all limiting factors combined. It is axiomatic in ecology that adaptation takes place to a suite of characters acting together, which implicates the "round-cake" model.

Scaling between distribution types

Intermediate cases between the "square" and "round" cases, presumed to represent physical vs. ecological constraints can arise from uncertainty and the availability of data for dimensioning the niche. It is thus a practical necessity to be able to scale between the two model types. Such scaling is possible using the single parameter, q, in Equation III-6, above.

The effect of this scaling for the same flattened response function is shown in **Figure III-8**, with dimensional isotropy on the left ("square cake") and complete anisotropy on the right ("round cake").



Niche hypervolume based physical (multiplicative) combination (q=0).

Response in X and Y applies to both "square" and "round" models, depending on q (0-1)

Niche hypervolume based on "ecological distance" (vector) combination (q=1)

Figure III-8: Idealized Niche Hypervolumes

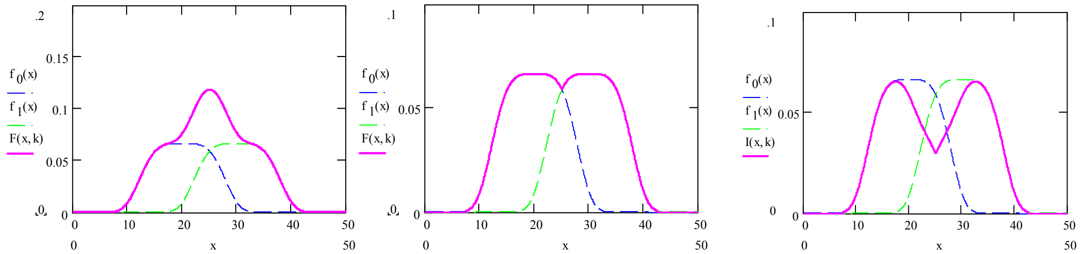
Combining Multiple Modes

Multi-modality can be expressed in the final niche hypervolume (and in each dimension separately) by combining the individual modified Gaussian functions

$$\textbf{Eq. III-7} \quad F(X) = \left[\left\| \left\| f_1(x)^{\frac{1}{|P|}} + \frac{p}{|p|} f_2(x)^{\frac{1}{|P|}} \right| + \frac{p}{|p|} f_3(x)^{\frac{1}{|P|}} \right| \ldots etc., \right]^{|P|}$$

(along any combination of axes) according to **Equation III-7**, when separate modes are defined. However, each mode along each axis, and therefore each mode in the final hypervolume, should be processed separately, deconflating the dimensional response curves into its separate modes (asymmetry notwithstanding). In this way, an unambiguous “ecological distance” vector can be established for each n-dimensional mode combining the axes, and also allowing independent parameters for each mode. The multiple modes of a function that may result may later be found to represent different species, or sub-species (or other functional components of a system) with inter- or intra-specific interactions that may differ between various modes. The n-dimensional modes can be combined by setting P~0 in Equation III-7, which is then easily applied to multiple modes and dimensions ($X=(x_1..x_n)$). The same technique can be used in more complex models to combine independent niche models according to the type of interaction being modeled, as shown in **Figure III-9**.

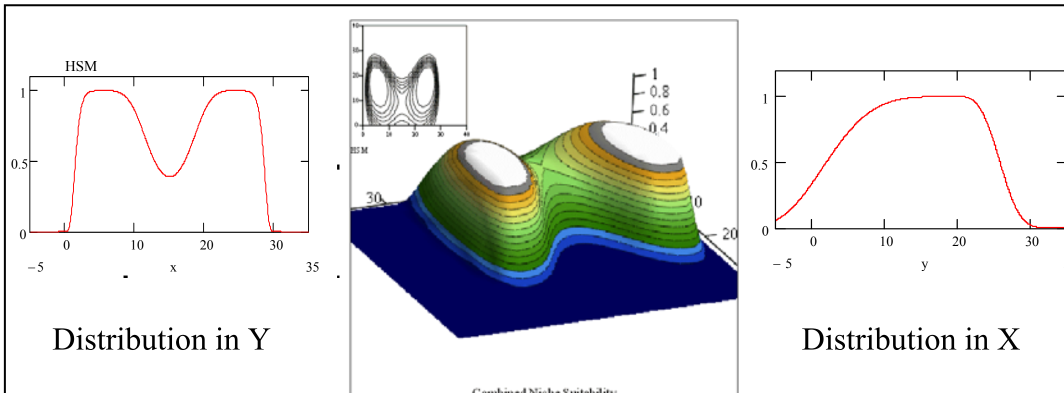
The parameter P specifies the degree to which multiple modes augment or diminish each other where they overlap. Also, using this technique, the amplitudes of each function, f, can be weighted (empirically or from some theory) for a given analysis. In the example here both functions are equally weighted.



P=1, synergistic P~0, null interaction P=-1, competitive

Figure III-9: Combining two modes using Equation III-7

P = 0 produces no additive effect (a logical OR condition), and thus traces the maximum of both curves. P = 1 produces addition (a logical AND condition) with increasing synergism above 1. Competition can be represented in this same form with P < 0, which reduces the function proportionally where it overlaps. P = -1 halves the amplitude where the functions are equal. P < -1 would apply in cases of strong competitive exclusion. Multimodality in one dimension can be combined with single modality in another dimension in separate or combined (hypervolume) axes, as in **Figure III-10**.



Distribution in Y Distribution in X

Figure III-10: Combined (multi-modal) Niche Hypervolume

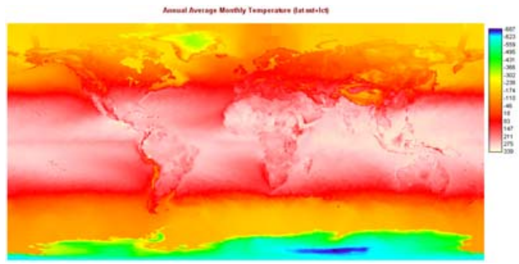
Test Results

Test 1: North American Picea (Spruce) Distribution

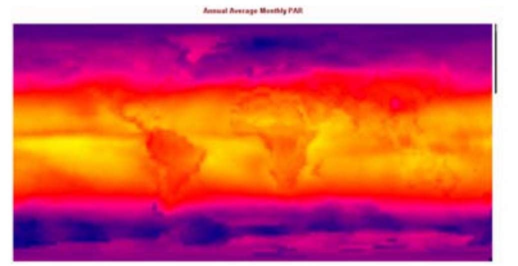
MGNC was compared with two other model techniques, a GIS overlay, and a more sophisticated model called *Biomapper* (Hirzel et al., 2002). Pollen count data were averaged for the recent century[25] and used as proxy samples to indicate picea (spruce) abundance in the sample area (northeastern US). These data (and that of prior Centuries) indicate a northward movement of spruce since the last glacial period in response to recession of the Laurentian ice field and associated warming. A Modified Gaussian Niche Composition (MGNC) model, as described above, was developed to characterize this distribution in temperature, precipitation, and photosynthetically active radiation (PAR). Sample abundances and construction of the response curve for temperature are shown in **Figure III-11**. Distribution of the combined response function (the MGNC model), is shown below, thus predicting potential distribution of the associated species across North America.

In the right-hand panel of **Figure III-12**, results are compared with GIS overlay, which produces an intersection of the ranges in the three dimensions. This is the same as multiplying uniform ranges (MGNC's Case II). It can be seen here that the intersection of uniform ranges significantly over-maps the distribution compared with MGNC, when set to map ecological limiting factors (Case III). In a similar comparison between MGNC Case III and *Biomapper*, with the same data, the initial correlation was very poor, but an excellent fit (r = .97) between MGNC and Biomapper outputs

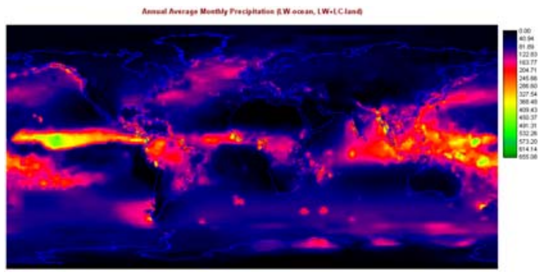
[25] Data obtained from the NOAA Paleoclimatology Program



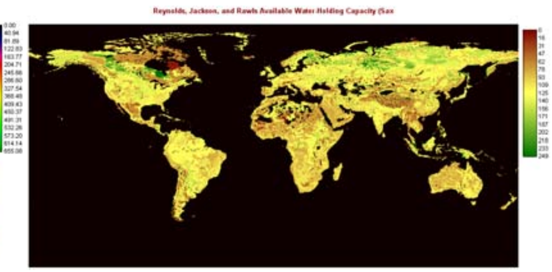
Temperature



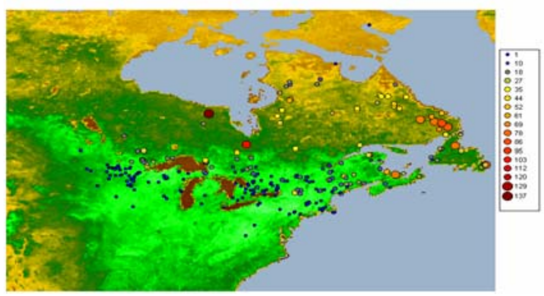
Photosynthetic Radiation



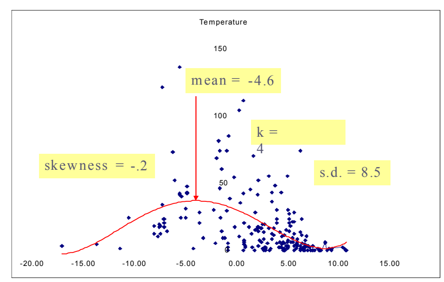
Precipitation



Soil Water Holding Capacity

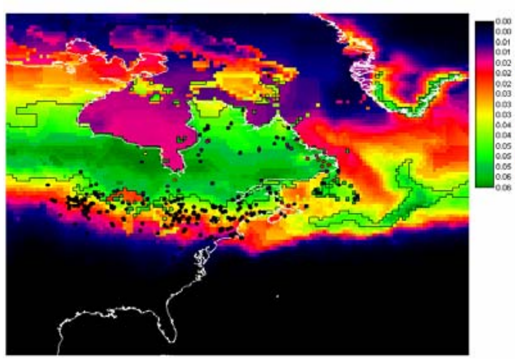


Picea, pollen count distribution

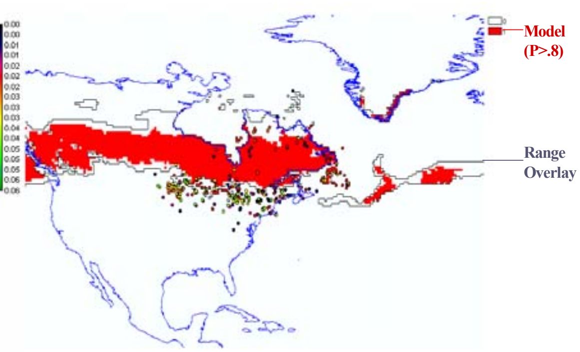


Example response curve (temperature)

Figure III-11: Estimating Modified Gaussian parameters for Picea distribution. Four independent variables were used (Top).

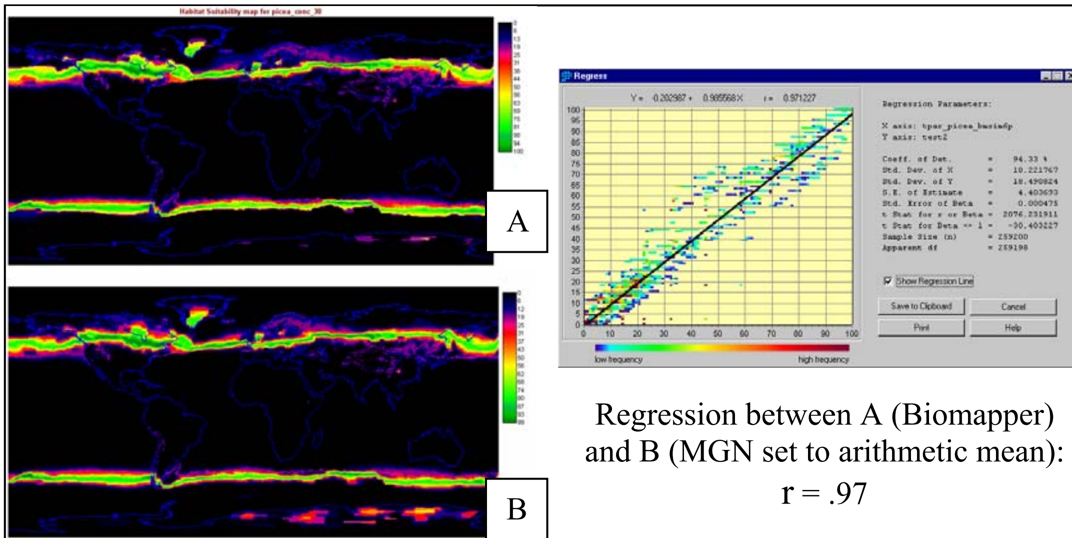


MGNC model for picea



MGNC (fill) compared with GIS range overlay (line)

Figure III-12: Modified Gaussian Niche model for picea (spruce) was obtained (**Figure III-13**) by setting MGNC to calculate the arithmetic mean (addition) of response functions for each axis (Case I in the Methods).



Regression between A (Biomapper) and B (MGN set to arithmetic mean): r = .97

Figure III-13: Comparison of MGN with Biomapper

Test 2: Vegetation Distribution in India with respect to climate.

A simple demonstration of the MGNC model was conducted using a global database to produce a potential map of the vegetation of India. **Figure III-14** shows the two dimensional hypervolume with flatness and skewness, and a corresponding intersection of the hypervolume along the x axis. The independent variables were temperature and rainfall (Leemans and Cramer, 2000) averaged during the growing season. Functional response curves were calculated using a satellite derived "Generalized Vegetation Index" (Kineman and Hastings, 2000) as a proxy for vegetation distribution. The parameters of the hypervolume were then

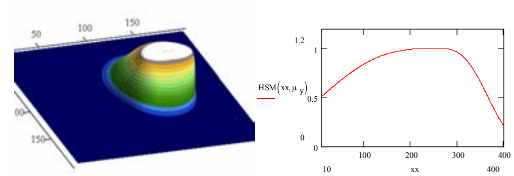


Figure III-14: Functional Response (Temperature & Rainfall) calculated for GVI response. **Figure III-15** presents the results mapped as contours. Because this climate-related potential vegetation would miss suitable conditions for vegetation along rivers in otherwise arid regions, a second model was created to capture potential vegetation in broad river valleys from runoff (red circle in diagram). This second model was produced from a geographic analysis of river location and terrain, considering rainfall. The two models were combined according to equation (2) with P ~0. The final result shows a good correlation between the model and satellite data (r=.6).

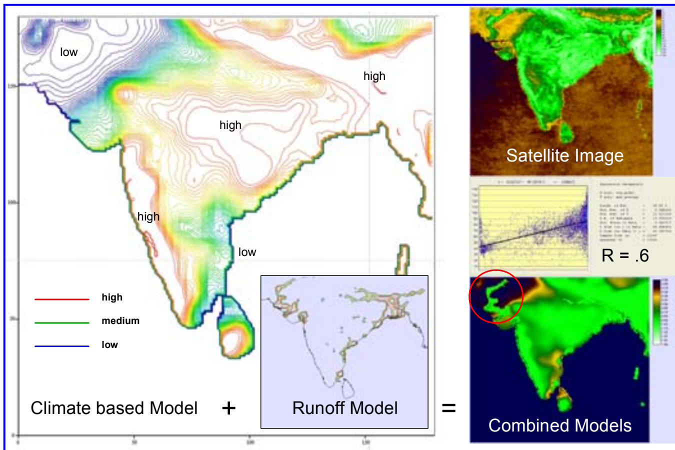


Figure III-15: Potential Vegetation Map (Model) for India

Test 3: Phytoplankton (chlorophyll-a) Distribution in Coastal Bays

An earlier version of MGNC was tested by Donatto Surratt with the author in a cooperative grant involving Florida A&M University's Environmental Science Institute, NOAA's National Estuary Research Reserve, and NOAA's National Geophysical Data Center. Results were reported in (Surratt, 2005b; Surratt, 2005a). This project determined potential species community (phytoplankton as chl-*a*) distribution via niche modeling on a regional (North America) and local (Apalachicola Bay) scale. Three niche modeling procedures were compared, including the early version of MGNC, a linear Habitat Suitability Model (Rubec et al., 1999), and Hyperniche, a non-parametric local-linear model (McCune, 2006).

The models were applied in three sets of trials to test hypotheses about their differences. In particular, we expected that local linear techniques will do well where the environmental range is small and the sample is well away from optimality (not at the peak of functional response) because under those conditions modal response is closest to a linear approximation. We also expected that non-parametric approaches will do best at modeling any actual data distribution, but will do poorly as predictors beyond the environmental range of those data; that is, in data poor situations where one wants to predict generally. That situation, we expected, would be best met with a theoretically general technique (which MGNC attempts to be) that can constitute a functional ecological prediction. MGNC was applied very generally, as a multi-modal composition of standard Gaussian forms, essentially testing the theoretical assumption of modality.

Surratt performed three trials comparing three models in each case. These trials were designed to test the analytical capability of the various methods and their general robustness across different locations. As cited above, (Elith et al., 2006) found considerable variation in each of many niche models with respect to location and species.

Trial I: In application of the models on the local Apalachicola Bay data, the linear HSM technique modeled 73% of the presumed variance (**Figure III-16**, top) Hyperniche modeled 50% of the variance, and MGNC modeled 29% of the variance.

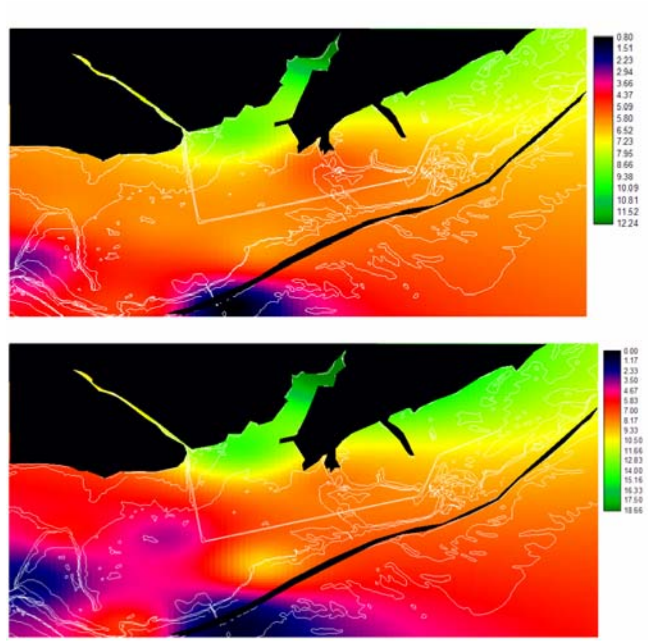
Trial II: Applying the models more generally, to data from 8 coastal enclosures around the Southeastern US Hyperniche modeled 97% of the variance in the empirical chl-*a* distribution data, MGNC modeled 51% of the variance, and the linear HSM technique modeled 3% of the variance. This provided a comparison of a best-fit-to-data method, a theoretical approximation that avoids "over-fitting," and a local technique that obviously exceeded the limit of local assumptions at this scale.

Trial III: Applying the general models (derived from the data for 8 bays) locally to Apalachicola Bay resulted in MGNC accounting for 89% of the variance (**Figure III-16**, bottom**)**, the linear model accounting for 73%, and Hyperniche accounting for 49%.

Site	Latitude N	Longitude W	Area (km^2)	Salinity Average (ppt)	Temp. Avg – C	Nitrogen (mg/L)	Chl a [10^{-3}] (mg/L)
Apalachicola Bay	29.64	85.09	260	19.8	24.1	0.11	5.5
Delaware Bay	40.95	73.67	1331	19.7	18.5	3.3	7.3
Galveston Bay	29.55	94.91	1300	17.5	20.93	0.86	7.7
Great Bay	43.07	70.88	47	40.2	15.4	11.2	7.8
Jacques Cousteau	39.51	74.34	189	17.7	17.1	0.04	4.4
Jobos Bay	17.99	66.24	31	29.8	28.7	0.26	0.56
North Inlet	33.33	79.19	157	30.32	19	0.021	6.4
Narragansett Creek	41.62	71.32	124	29.98	13.97	0.27	2.13
Mean for all bays			429.88	25.62	19.71	2.01	5.22

Table III-1. Physical and chemical properties of the eight systems modeled (Surratt, 2005a)

These results generally confirmed our expectations. In particular we can reject the hypotheses that either linear or non-parametric models make good predictors beyond the range of sample data, if samples do not cover the full range (and hence if the full range is not known in advance). While a Gaussian decomposition is also sensitive to mode detection, it can be estimated from sparse data and the technique



Figurue III-16: Linear HSM using Apalachacola Bay local data (top) and MGNC using regional data from 8 coastal bays, re-applied to Apalachacola Bay (bottom). (Surratt, 2005b)

ends up being more robust across different conditions. Apalachicola Bay is about average for all bays in phytoplankton density (minimizing concern about density-dependent factors), but it is well away from the average in both temperature and salinity, placing it on the edge of the overall adaptive range. This can explain why the linear HSM modeled the distribution best in Trial I, whereas MGNC did not have sufficient information to locate the true mode (it was set equal to the local average for this test) and Hyperniche presumably suffered from the sparse and heterogeneous data sampling. McCune stated:

> *"Despite the improved fit to responses near the ends of the ranges of predictors, local linear models are less conservative, and can produce wild estimates under some circumstances. They are less conservative, because estimates of the dependent variable can be outside of its observed range. This behavior can be particularly noticeable and offensive with small data sets." (McCune, 2006)*

In Trial II, the non-parametric fit to the data across all systems achieved best accuracy, we presume because of better sampling of the environmental range. The linear HSM failed miserably in this case because the environmental range was wide enough to reveal a modal response, where linear regression is clearly inappropriate. Its rather good performance when applied back to Apalachicola Bay suggests an underlying broad linear response in the data, or coincidence with skewness (which was not tested). MGNC performed significantly better on the general data in Trial II than it did on the local data in Trial I, suggesting that it benefited from the wider environmental range that revealed the modal distribution expected from niche theory (which turned out to be multi-modal). The most interesting result was in Trial III, where the general models were applied locally to Apalachicola Bay. The general MGNC model was tri-modal in temperature and salinity, and uni-modal in nitrogen, whereas only single modes were detectable in Case I. This suggests that as we broadened the environmental range across 8 bays, we also encountered different community adaptations to those local conditions. Nevertheless, mode detection doubled the model's precision and when applied back to the local conditions of Apalachicola Bay it produced a significantly better result than the other general applications. Furthermore, this result was attributed to only one of the modes in the tri-modal general model, suggesting that the broader set of data helped identify the assemblage in Apalachicola Bay and distinguished it from two other hypothetical assemblages. This suggests that indeed MGNC can be effective in testing hypotheses about functional response and in distinguishing adaptive components of a distribution by modal decomposition. The fact that the general non-parametric model decreased its performance by nearly half when applied locally suggests, as expected, that it is more dependent on sample distribution and less analytical of ecological relationships.

In certain studies, as in this case, if the range of environmental variability in a given study area is such that the peak of the true ecological response does not fall in the range, the Gaussian modes (modified or otherwise) must be inferred outside the range of data, an uncertain but not excluded procedure. This was not done in Trial I, affording a test of purely local applications of the three different techniques. It is obvious that a modal function set to the average of a set of data rather than its true mode will be a poor model, but this example serves to demonstrate what some probabilistic methods will in fact do if applied without knowledge of their parametric assumptions (i.e., Gaussian probabilities based on calculation of sample mean and standard deviation, as is common in probability models).

In cases where the samples are far from the mode the response function tends to flatten and it is common to model it with a geometric mean of linear response functions, as in the linear HSM method tested here (Rubec et al., 1999; Davis and DeLain, 1986). When two linear functions are multiplied, the result is a curvilinear (parabolic) surface, as shown in **Figure III-17**. A more circular shape can be obtained by using the "ecological distance" method of combining the axes in MGNC.

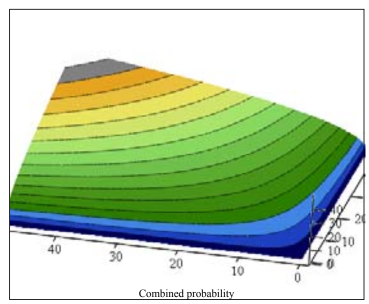


Figure III-17: Local linear multiplicative model

Linear response functions are poor approximations of general conditions, but they can be used as piecewise locally adapted models, as Hyperniche does to produce a "non-parametric" result, and they can be used where the range of data being modeled occupies only a portion of a larger modal distribution. Surratt's results support the conclusion that Apalachicola Bay represents a sub-optimal region of larger modal distributions. An interesting follow-up to this study would be to conduct laboratory experiments to determine the full range of response for the specific assemblage in Apalachicola Bay, comparing that with the general MGNC model.

Discussion

The MGNC model was designed for integration into ecological informatics as a general method for describing the contextual limits on structure and function; that is, to describe the distribution of potentials in environmental and geographic spaces for theoretical and empirical studies. Its use for mapping ecological distributions is a means to that end as well as a potential management tool. Preliminary tests reported here, and literature cited, suggest that improvements in how niche modeling represents ecological theory, and clearer interpretation of inputs, model assumptions, and outputs, may be more productive than enhancing statistical precision. Both limitations of available data and natural complexity limit the extent to which statistical description, on its own, can inform us about ecology.

For these reasons it is important to design a niche modeling technique from the start as a means for iterative testing of hypotheses, which may be related to ecological theory or specific biogeographic distributions. Parametric methods, aligned with elements of ecological theory, seem to offer the best chance for broad application to ecology and integration with eco-informatics. Non-parametric methods can typically produce a better fit to sample data, but does not necessarily provide a better representation of the ecology without proper interpretation, which includes consideration of dynamics and complexities.

The global or regional scale of the tests reported here undoubtedly simplifies the factors needed in the model to produce a good correlation. Finer scale application can be expected to be more challenging due to more factors, dynamics, and heterogeneity. Further testing of MGNC is thus needed to properly compare its performance with other available techniques. Nevertheless, these initial test results indicate that MGNC is capable of reasonable results and is perhaps easier to use properly because of its simplicity and explicit assumptions. Most current models have vague ecological assumptions and are unclear regarding the appropriate character of their inputs and ecological meaning of their outputs. As with all other techniques, the primary uncertainty in MGNC lies in factor selection, establishing valid response functions, and combining dimensions appropriately for the type of data and type of distribution being modeled. Other than that, it is conservative and robust (in an ecological rather than statistical sense) compared with other techniques. The greatest improvement is likely to be obtained from making these steps explicit and clear, and embedding the niche model within a suitable architecture to support iterative testing and application to dynamic simulation of natural relationships – a much expanded use of niche modeling as first a research tool in ecology and second an informatics tool for management.

MGNC has no capability for evaluating factors or selecting them. This is left to other methods, expert knowledge, and iterative testing. Linking its application with statistical tools for determining likely factors, and for calculating the model's parameters is therefore necessary, but easily accomplished in available software. A more robust technique for Gaussian decomposition than has been explored here might be a very useful addition, to aid in resolving ambiguities that are certain to arise in how to decompose an aggregate response function. Nevertheless, MGNC's accessibility to visual interpretation is meant to employ expert opinion in the process of decomposition. It is likely, for theoretical reasons, that no exact method of automating this can be devised because the decomposition of ecological functions is inherently semantic, involving meanings in nature as well as the ecologist's question and thought process. When to split or combine modes relates directly to how one classifies or defines biological entities and functions, and that relates directly to the purpose of the analysis, which may exist at any functional scale from selective behaviors of individual organisms to aggregate clusters of ecological functions representing ecosystem services. Indeed it is the very purpose of this approach to facilitate such broad possibilities.

Test 1 suggested that the dimension variables were being interpreted by *Biomapper* as indicators of presence of the target distribution, rather than as mutually restrictive niche factors, as one might expect for an ecological niche specification. While not invalidating *Biomapper* for use with indicator data, this result emphasizes the point that ecological interpretation should be supported throughout the modeling process, from definition of variables and their meaning, to ways of factoring them together, and to the intended meaning of the output.[26] The intercomparison was also useful in evaluating MGNC's ability to clearly distinguish the assumptions being made. MGNC is explicit in its assumptions that organisms, and organism-based living functions, relate holistically to eco-physiological controls, multiplicatively to purely physical constraints, and additively to indicators. Each of these conditions can be represented as model options in MGNC, for greater flexibility in modeling different kinds of distributions, and also to provide intermediate cases where these distinctions

[26] Newer versions of Biomapper (Hirzel et al., 2006) were not tested, and may perform differently.

may not be clear in the data or type of analysis. Using an intermediate case does not preclude the possibility of exploring decompositions later.

In practice, the niche can be constructed by estimating response functions from samples using standard statistical techniques. But in the tests it was also evident that expert knowledge could be used almost as accurately to visually estimate the niche parameters for each response function. With targeted iterative sampling, estimation of the parameters can converge on presumed equilibrium distributions or detect and track dynamics.

The MGNC model is maintained in measurable environmental space. It does not require, nor can it be significantly improved by translating the niche variables into an orthogonal vector space ("Eigenspace"). Natural codependency of the variables themselves has no effect on mapping the geographic distribution of the general hypervolume, because only those combinations of factors that actually exist in the data will be mapped. In this case, however, the distribution in theoretical space will be greater not show this difference. Biological co-dependence, if present, will matter, however, and should be incorporated. A special form of biological co-dependence, in terms of the 'round cake' model, is presumed to be characteristic of purely adaptive biological distributions. However, less symmetric biological codependence, either positive or negative, can be an added factor that further limits the final distribution. Such co-dependencies are difficult to discover and test with typically poor initial data. The modeling approach is explicit enough to allow iterative testing for such co-dependence. In fact, the first map could be used specifically to target sampling for this purpose.

Combining Models

The general form for applying the MGNC model in an enhanced informatics architecture can be written very generally as (**Equation III-8**):

$$\textbf{Eq. III-8} \quad S_i = \frac{1}{N \times M} \sum_m^M \sum_{n=1}^N w_{(n,m),(N,M)} \times F_{(n,m),(N,M)} \left[[G_{n,m}(v_n, \mu_{n,m}, \sigma_{n,m}, \kappa_{n,m})], c, q \right]$$

where:

S_i is the suitability in n-dimensional niche space for a given entity, *i*.

F is an algorithm to combine the modes (m) of the niche hypervolume, combining axes with parameters for covariance (c) and 'wholeness' (q),

w is an empirical weight for each mode, F, in the suitability landscape

G is the functional distribution in each axis (n) for each mode (m) from a deconvolution of Gaussian modes, where each mode is specified by three parameters (μ = mean, σ = std. deviation, κ = flatness), or, if asymmetric, as two half-modes with corresponding parameters.

v_n are the niche variables for each axis (n), corresponding to geospatial data as a function of space (x,y,z) and at a given time step, t.

G is an algorithm to combine co-occurring niche models (j) into functional clusters (taxonomic groups, communities, ecosystem services, etc.), with several ways of combining them (synergistic, neutral, exclusive).

We can then map S_i to geography, with implicit time defined by the data, by **Equation III-9**,

$$\textbf{Eq. III-9} \quad M_t(x, y, z) = H(S_i)$$

where:

M is a geographic map of the function in three spatial dimensions at a given time step, t, and

H is an algorithm to map suitabilities (S_i) to geographic space according to the spatial distribution of the niche variables (v_n).

Introducing Dynamics

An explicit representation of time can be introduced in two ways. First, time-series data will drive the suitability map dynamically, or update it to new conditions. Second, ecological dynamics can be introduced by employing the niche model as a means of specifying the application of the organic function itself to those state variables it modifies. In the case of a species niche, this would mean applying a model of what environmental changes the species' presence represents, including that presence itself. Such changes feed back to the database used for niche factors, producing a complex dynamic. The result is similar to what exists in cellular automata or agent-based simulation (Box, 2002).

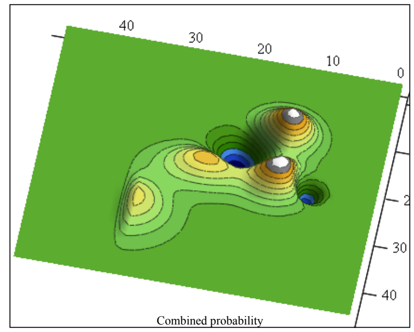
In geographic space S can be interacted with other niche functions (for example, as species or other functional interactions) to simulate dynamics that do not assume co-location; that is, to consider interactions between S_i's, v_n's in three spatial dimensions (x,y,z) and pseudo time (t) for iteration of the relationships. This allows simulation of how different configurations of functions will develop and how they will alter variables, with feedback to their own suitabilities. This can be expressed in according to **Equation III-10**, where: H is an algorithm to combine functions (f_i) constrained by their suitabilities (S_i) to represent direct functional interactions, such

Eq. III-10	$I(x,y,z,t) = H\left(S_{i=1 \ldots I}, f_{j=1 \ldots J}\right)$	where, I is the total configuration in geographic space (x,y,z) and iterative time (t)

as predator-prey interactions, or competition/cooperation; or to represent indirect selection or optimization, as attractive potentials between different systems realizing a given function and different functions of a given system (see introduction).

Geographic Relationships and Dynamic Adaptive Landscapes

Being a mathematical function of n-variables, an MGNC model can be easily mapped in an analytical GIS, accessing appropriate map layers for each variable. Once the niche space has been translated into geography, it is then possible to introduce geographic constraints and interactions between models. Suitabilities for two functions or species, for example, can be combined and weighted according to their relative strengths. The parameter "P" in Equation 5 can be used to scale from competitive (exclusionary) to synergistic (additive) interactions. This is where the various Cases listed above can be combined or interacted dynamically. A purely physical distribution constraint can be mapped using Case II techniques, and then intersected with an ecological niche model from a Case III analysis. A species distribution can thus be limited, for example, by a model of land development or the dispersion of a pollutant. More complex biological interactions, say between a predator and a prey model, can be simulated, while allowing both distributions to appropriately modify environmental conditions, perhaps from foraging or trampling or nutrient enrichment. The architecture can thus be used for complex ecosystem simulation and forecasting. Whether the decomposed elements are represented dynamically or as equilibrium potentials, a very complex adaptive landscape can be mapped, as in **Figure III-18**. By including negative Gaussian models, areas of known exclusion for a given phenomenon can be represented, thus assigning a suitability value of zero to the meaning of neutrality or uncertainty. For example, such a surface can be constructed for prey species of a given ecosystem where negative suitability represents areas of intense predation (perhaps hunting) or other pressures.



M **Figure III-18:** Adaptive Landscape of Combined Niche Models

Implementing the Architecture

Figure III-18 shows how the niche model can be embedded with a database architecture in a manner that allows iterative testing of the model, and iterative application of the actual functions that the niche model distributes environmentally and geographically. The iterative loop indicated by blue arrows in the diagram shows how model application changes the database and in turn alters the model to the extent that its limiting factors were affected by the distributed functions. This establishes a "direct" relationship as referenced in the Introduction. The causal loop (blue arrows) represents a formal 'impredicativity,' which can only be resolved by iteration on arbitrarily small intervals and in sequences that may approximate nature's more simultaneous or time-dependent interactions. For example, the effect of predicted species movement on a species density map in the database (a possible niche factor) is theoretically simultaneous, whereas the effect on nutrient availability should be time-dependent. Through appropriate iteration, multiple instances of models can be interacted in geographic space, updating conditions in the database stepwise, thus simulating dynamics in both dependent and independent variables. As indicated in the figure, this can proceed independently of improvements in the database, and additional dynamics can be introduced by adding time-series data, for example from seasonal, annual, or other climate change.

"Indirect" relations, as discussed in the Introduction, are also indicated in **Figure III-19**. These relationships involve mutual surrogacy between taxonomic functions and those systems that produce them, for which the niche model is being created.

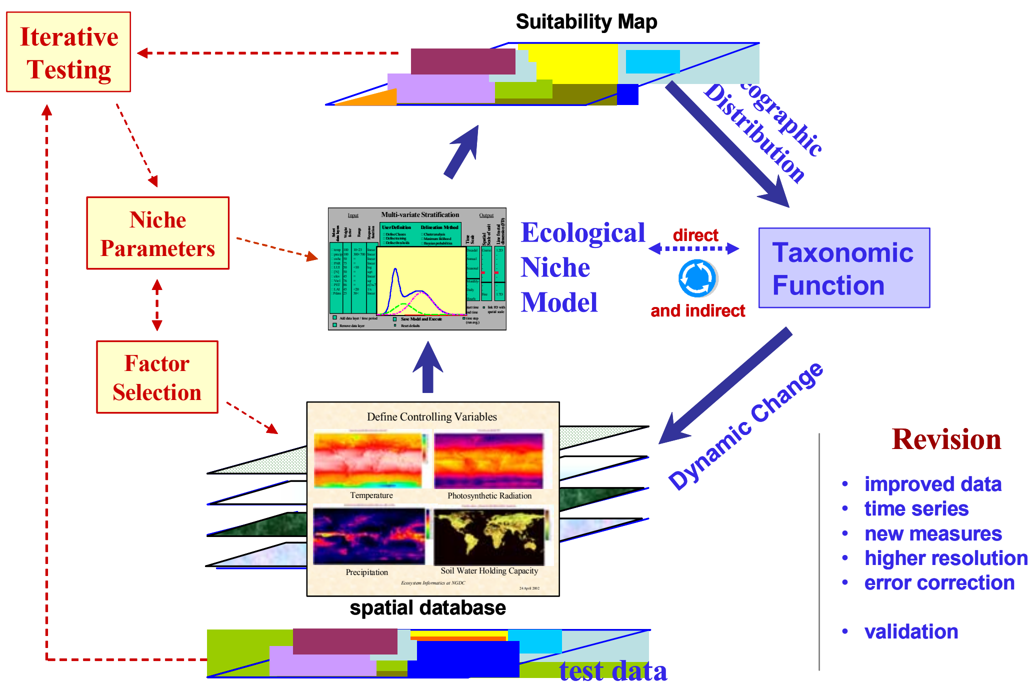


Figure III-19: Niche Model Architecture

Entailing Structural and Functional Niche Relations

It is now appropriate to pick up the thread on which the discussion of relational complexity and the niche concept ended in the Background section; the understanding that niche models applied to the relationship between structure and function are equally valid in either direction. In other words, ecologists may be comfortable with the idea that a niche describes the fit of an organism as a functional unit, into an environmental space of related (structural) factors; but it is equally true that organisms, as material systems, are generally identified by their structures and can be said to exist in a selective space of related functions. For convenience we may call this inverse relation the *"structural"* niche. As previously mentioned, the same niche formalism as that of the functional niche will apply, were a function space limits the realization or attraction of structures. This conclusion follows also from the idea in relational theory that structure and function are essential compliments of each other—two aspects of a unity that is a natural system component. It is the relational epistemology that separates structure and function for analytical purposes. As such these empirically accessible aspects appear in a many-to-many relationship with each other. It is perhaps easy to imagine the niche as a material limit on the geographical expression of a function. The inverse is a set of potential structural realizations (adaptive entities than can perform various functions) being attracted according to niche model suitability in a dimensional space of functional needs (*'function-space'*). In each case one aspect is held in focus while the other is generalized as a general system potential, as the nature of a complementarity requires. The resulting suitabilities can be mapped to geography through the distributions of the limiting variables. By including both structural and functional niches in the architecture, it then becomes possible to drive each with results from the other, where complex simulations or other queries are needed. When both forward and inverse niche possibilities are considered, we can then specify an information entailment that is capable of reflecting the presumed natural condition in relational theory. What we accomplish in the analysis of structure and function is to represent the complex aspect of their relationship that is otherwise hidden in the ontology: the fact that a structure can have many functions and a function can be actualized by many structures. This is the “indirect” entailment discussed in Chapter Two. Any niche model itself represents the contextual entailment (“control information”) of relational theory, which comprises empirical associations between actual systems (structures) and their known functions.

Figure III-20 shows a very simplistic (hypothetical) relations, direct (actual) or indirect (potential) connecting multiple structures with multiple functions for a variety of entity types. Examples of functions performed (blue arrows) and functions required (red arrows) are shown. The inverse relations are implicit in reversing the arrows. The many-to-many entailments, if implemented in a relational architecture, could be used to search for functional diversity and redundancy, compare relative strengths of functions and needs, and identify structural and functional replacement potentials. Each of these relations is subject to the contextual control expressed by corresponding niche models. The potential and obviously actual relational linkages grow rapidly with the

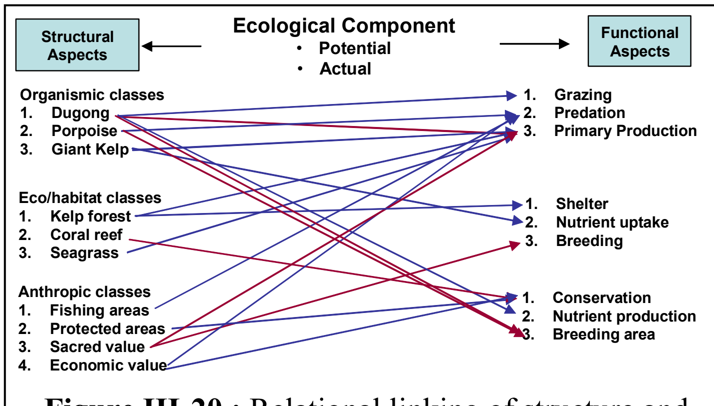


Figure III-20 : Relational linking of structure and function. Blue indicates functions performed, Red indicates functions required.

combinatorics of such a diagram, and hence they require implementation in a sophisticated DMBS architecture, which can also make the links to niche models and their necessary components. Entities of all types can be recorded in this manner, defining different types in separate tables for efficiency and convenience and identifying an appropriate contextual (niche) model type, as discussed above. A architecture designed along similar lines has been demonstrated by (Marcot and Vander Heyden, 2001; Raphael et al., 1998; Marcot et al., 2002).

Figure III-21 shows a basic (hypothetical) schematic for how these relations may be implemented in a database schema. To resolve inherent circular references (impredicativities) in the relationships, a method of iterative sequencing and storage (via the structure and function databases) must be introduced in the method of query.

The overall architecture thus relies on relationships between taxonomically defined biological or ecological systems, the functions they produce or require, and measures (structural abstractions) of their material nature. Consequently, five kinds of database are required:

1. Descriptive database of biological or ecological classes (taxonomic base)
2. Descriptive database of biological or ecological functions (function base),
3. Prescriptive database of niche models
4. Spatio-temporal database of structural suitability (in a function space)
5. Spatio-temporal database of functional suitability (in a structural space)

The function-base should ideally contain dynamic models (which can be mechanistic) for the execution of the function (which is a specification of state change). Since this kind of information may be limited, there will be many cases where only a general description of the function is available, such as “foraging” or “decomposing.” The lack of a mathematical model will obviously prevent simulation using that function; however, it does not diminish the value of the information for informatics purposes. As demonstrated by Marcot et al. (works cited above), complex queries can be made, and distributions mapped, to analyze a variety of complex ecosystem factors, such as functional overlap, critical function dependencies, inferred stability and resilience from functional redundancy(Marcot et al., 2002). As one defines higher order taxonomic groups, and thus diverges from fundamental relationships at the organismic level, one can expect increasing generality of results,

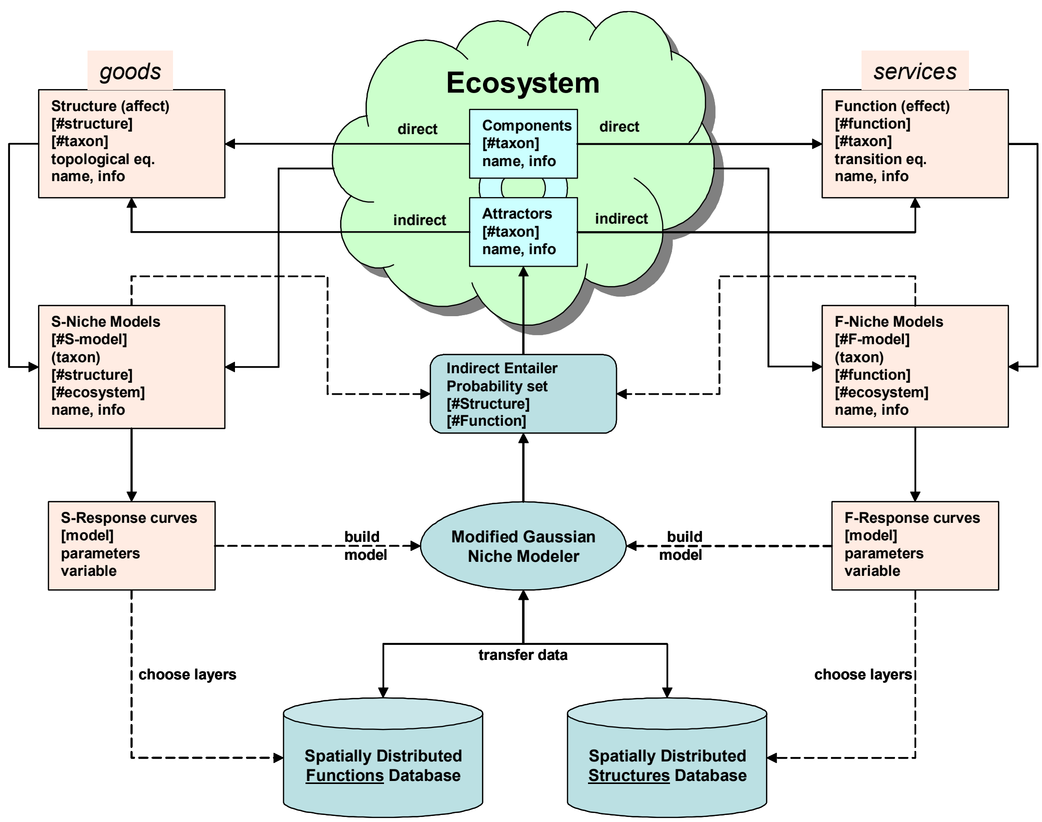


Figure III-21: Relational Architecture for Structure-Function Entailment but also the possible introduction of new phenomena at these higher holarchical levels.

The function-base can be implemented using existing geospatial architecture in a similar manner to a common “entity-attribute” table, applying this idea instead as a “model-attribute” table. Attribute tables can then contain the qualitative description and labeling of the function, parameters of a model for its operation (if available), and metadata about the function and/or model. A similar table can store the name and details of the niche models used to relate structures and functions, referencing separate tables and databases for the functional response parameters and variables used. In this way the system is able to represent functions in relationship with familiar state variables, as described in the Introduction. **Figure III-22** shows a typical query in Arc/GIS of an entity-attribute table. The analogous “model-attribute” relationship is written in to show how it might be implemented.

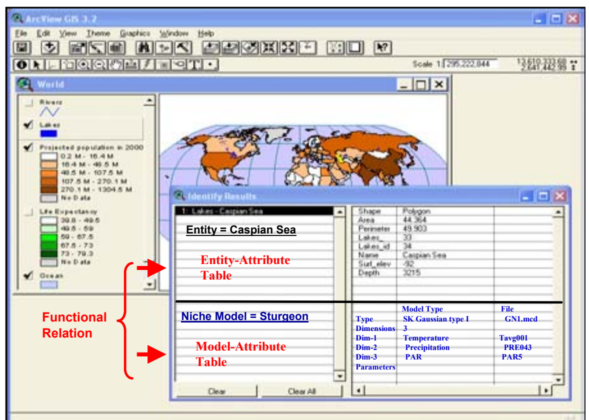


Figure III-22: Model–Attribute Table

Conclusion

In this chapter, I explored a general approach to niche modeling for two purposes; first, to provide a general theory-based method for exploring causal relationships responsible for ecological distributions, second to provide a general and robust means for mapping all kinds of functional distributions on the landscape, and third to serve in the design and architecture of relational informatics as the means for representing complex entailment between structure and function. The approach was derived from basic Hutchinson/McArthur ecological niche theory and existing statistical methods, but considering the requirements of Rosen relational complexity theory concerning the entailment structure of organism and ecosystem relations. That theory supports the traditional view in ecology that the interaction between self-entailed, adaptive systems, which organisms are, and their environment can be studied as an interaction between a whole functional component and its context, decomposing that relationship into niche dimensions that each describe of modeling relations that are theoretically non-fractionable. Such components interact and adapt as wholes, such that analytical components of the interaction arbitrarily defined along separate axes act together, not separately. This places greater limits on the method of combining McArthur "resource" axes than a statistical or physical model would suggest, providing a potentially sharper method for predicting the holistic response. The broader application of niche models to potential relations allows for higher system properties to select components based on mutually defined relations, or to replace components with functional equivalents. The relational theory requires a general method for representing indirect entailments corresponding to structural and functional possibilities, and regulation of structural and functional expression by context. To perform in all of these roles, the method must be simple, theoretically valid, and robust across all kinds of adaptive systems; and it should support hypothesis testing at the level of its dimensional factors and response functions. The use of niche modeling in relational informatics is to scientifically model contextual relations, not merely to estimate distributions. For this reason its construction must be testable in an experimental context with respect to causal factors. Statistical modeling procedures that provide only an overall fit do not allow such testing, nor can they accept the input of knowledge from other sources than sample data. For these reasons a parametric technique is recommended that allows for decomposition of theoretical sub-components in terms of modified Gaussian forms.

Three types of dimensional synthesis were defined in MGNC: Case I for statistical indicators of presence which are additive, Case II for physical constraints with are multiplicative ('square'), and Case III for true ecological niche models that are in theory isotropic ('round'). Isotropy is maintained by parameterizing the hypervolume along an "ecological distance" vector centered about a mode. A method was derived that is decomposable to this theoretical case, and yet constructible and scalable between physical and ecological cases to accommodate mixed or uncertain situations in actual studies. Thus the functional niche concept presented here allows for adjusting the method of hypervolume construction, along a continuum of system types from physical to ecosystemic (mixed) to organismic response types by specifying a single parameter (q). Ecological niche modeling may thus be generalized as functional niche modeling, which can then realize its full central role in ecological theory and informatics. Functions (which specify state change) and the niche models defining their environmental regulation and thus geographic distribution, may be integrated or decomposed to model hierarchical phenomena.

The niche model can be used to represent both "direct" (realized) and "indirect" (potential) entailments in an informatics system, linking structures and functions in complex ways for information retrieval and to support advanced modeling and simulation possibilities. The approach makes it feasible to construct an ecological informatics system that relates environmental, general taxonomic, and functional databases.

The MGNC method seemed to produce good results in early tests and seems able to robustly preserve ecological interpretation in all of its components. The model's generality and parametric specification open it to multiple sources of information for determining niche response, including iterative testing, laboratory experiment, and expert knowledge.

The approach recognizes in a very important way, that the fundamental niche, interpreted here as the *'formal'* niche (in keeping with the idea that it specifies the operation of a function) is different from its realization. It is an explicit "potential" whereas, the '*realized*' niche is the result of historical conditions as they have occurred, generally from the effect of multiple co-existing potentials operating together in specific circumstances. The formal niche is therefore theoretically real, whereas the realized niche is a mere instance of its dynamics at a point in time.

The essence of complex realization is that functions and the systems that produce them can indirectly relate and select each other. Change occurs (attraction of niche occupants, modification of the environment, etc.) as functions operate on the configuration, i.e., the structure of the ecosystem. Because the dynamics result from the action of niche-constrained potentials, as in its attraction of occupants, there are loop causalities between the formal niche and realized distributions that can only be taken into account iteratively. Again, this discussion emphasizes the importance of distinguishing between the distribution of functions (their overlap, replacement, redundancy, selection, etc,) and the dynamics of functional expression (growth, dispersal, competition, predation, and other interactions), combining their effects but not conflating their causes.

The techniques presented here are robust and adaptable to many situations; however care must be taken to match methods with problems. This applies to selection of variables in accordance with the nature of the distribution one intends to model. Niche models can be used to represent the complex entailment of relations in a more complete, robust, and communicative ecological informatics enterprise if the following goals are kept in mind:

- Use of an appropriately general and robust functional niche model approach,
- Storage and attributing of functions in a taxonomic “function-base” (expanding the taxonomy to include functional clusters and ecosystem types),
- Storage and attributing of niche models in a “relation” base,
- Storage and attributing of environmental gradients in a database,
- Linking niche models with their dimensional variables from the database,
- Linking functions with systems that realize them, and vice versa,
- Applying functions, weighted by their niche models, to modify the database,
- Applying functions, through niche models, as attractive potentials for organisms
- Iteration of these relations for complex simulation and scenario building.

Chapter Four:

Implications of Relational Theory for Ecosystem Geography

Ecosystems and Eco-Units

Abstract

Ecosystem management poses tremendous challenges that ecological informatics will have to meet. To do so it must deal with living system complexity and explore new modes of thinking. The challenge facing ecological informatics today is to build information systems from an understanding of the nature of living system complexity, so that complex behaviors can be properly represented. One area where complexity becomes apparent is in the definition of ecosystems, eco-regions, and eco-region boundaries. A review of current theory and methods in biogeography and landscape ecology for ecological mapping suggests that the concepts and methods that have been employed are highly diverse and largely incompatible with each other. Theoretical integration may be possible if a common framework for understanding ecological units can be established. Such a framework exists in the ideas of relational complexity theory, viewing ecological units in terms of complex natural modeling relations. This approach provides an integrative framework for defining and mapping ecological distributions and eco-unit boundaries as structure-function relationships. Critics of the exclusive use of quantitative methods in eco-regionalization have correctly stated that the important sense of place, function, and meaning in geography and landscape ecology, which can be captured in expert knowledge, cannot be duplicated by databases and computers. Relational theory,

however, provides a way to relax many of the mechanistic limits, such as inattention to living or sociological functions, to better blend expert knowledge with computation and to otherwise employ qualitative with quantitative methods. The goals of interdisciplinary science require such an approach and a corresponding integral philosophy to support it. The conflicting approaches to mapping ecological units may be combined, for example, in a generalized method for functional (potential) and structural (observed) niche modeling and mapping that leaves critical definitions (system semantics) more open to expert opinion, analogy, and use of prior inference. This approach can be used for defining functional units (from ecological to anthropological) and for modeling functionally-determined distributions, providing an important component in a broader relational approach to eco-informatics.

Introduction

The new field of ecological informatics, which deals with the nature and application of ecological information as an intimate part of ecology, faces difficult challenges scientifically, politically, and culturally. Demands for more comprehensive knowledge than has been possible before have led naturalists from specialized interests in living forms to concern about whole living systems, including mankind. As social, political and scientific priorities shift to questions about systems, many of our terms of reference need to change; for they were defined during an era of mechanistic rather than complex system thinking. In the environmental sciences, emphasis has been overwhelmingly placed on the study of physical systems and as a result many of our concepts are defined in a way that is not well suited for thinking of living systems. We are generally at a loss to find appropriate theory and methods for understanding them, and woefully behind in even recording the available facts about them. Consequently, our increasing dominance of living systems is not producing the same kind of prosperity that characterized our scientific and technological relationship with the physical world. The green revolution has been nothing like the industrial revolution, (although there are many promising and many unexplored possibilities). Instead, we are encountering unexpected side effects and ecosystem feedbacks from human dominance that we do not understand.

The way we define nature and natural entities has a lot to do with how we think about nature and what limits we will encounter in our understanding and interaction with it. Advances in theory can help if they lead us away from strictly object-oriented views of nature inherited from the physical sciences, to a relational view that is more comprehensive and appropriate for thinking about complex functional entities. At the same time, we should re-examine our terms of reference—how ecosystems and other ecological units, including human landscapes—are defined in the emerging context of complexity science. Indeed ecology seems poised for an explosion of new understanding, as a result of its unique and critical placement at the interface between the physical and living, formative, world.

The emerging field of ecological informatics is called to meet these challenges with new approaches that can communicate natural complexity and thereby provide better support for science and decision making. Current ecological informatics should be expanded to produce a more theoretically complete information design that reflects natural complexity. In Chapter Two, I proposed that relational complexity theory can provide a suitable foundation for this change in terms of implicit modeling relations in nature and corresponding *"structure-function"* relationships in informatics. Ecologists will be familiar with these terms, but relational theory now provides a tool for defining and relating them, and for understanding their connection with an underlying ontology that comprises information relationships *in nature*. That theory offers new thinking about the foundations of ecology, and a more general view of nature and living reality, including human functions and values (Kineman, Banathy, and Rosen, 2007).

In science the new rarely if ever abandons the old wholesale. Knowledge is extracted and re-cast in new molds; and in ecology we can find many ideas that are already cast in relational concepts. The field has been driven in that direction by the necessities of its subject, while gazing guiltily at the comparative rigors of physical science. But in limiting its methods to those of another field it may have missed a rigor of its own, one that very likely can improve all of scientific thinking from the living to the physical.

Here I explore implications of relational thinking for current and historical terms of reference in eco-regionalization and ecological mapping, as one step toward establishing a more robust *"ecosystem perspective"* (Kay, 1997) in science and informatics. Many of these ideas are already on the road to relational rigor. I begin therefore, with a review of the history of ecosystem and eco-unit concepts and then explore the nature of ecosystems in relational terms. Much of this discussion focuses on the theory and practice of "ecosystem geography" (Bailey, 1996), the science of identifying and mapping ecological units for analysis, monitoring, and modeling purposes. We will see that a tremendous diversity of ideas has existed about what ecosystems are and therefore how they should be represented. Nevertheless, in the light of relational theory, these various concepts can be categorized and integrated, leading to clear recommendations for ecosystem informatics of the future.

Most ecologists find it necessary to think in terms of the connection between evolution, which represents the ontology of a living system, and ecology which represents the phenomenology of a living system. In the relational theory, the ontology of a system exists as an implicit complementarity between adaptive ‘models’ that are part of all living systems, and their actualization[27] in ecological terms (Chapter Two). Natural models confer a quality of mind to nature itself (Kineman and Kumar, 2007). This inherently Eastern perspective—mind in nature—is not antithetical to ecology or other science when it is explained in terms of natural relationships and information theory. To the contrary, it furthers the linkage between ecology and human sciences that has become the aim of landscape ecology (Forman, 1995).

Ecosystems are encountered as phenomenal expressions of ecology, but nevertheless reflective of the underlying ontological complexity expressed through organisms and perhaps existing in prototypical form at the ecosystem level. As Gregory Bateson taught, it is “*patterns that connect*,” (Bateson, 1979) and ecosystems are first and foremost defined by pattern, both physical and ecological. Physical pattern may bring organisms into association or limit their distribution, while ecological interactions between organismic components form the character of the ecosystem – *or is it the other way around?* Do ecosystems inform and shape their components as organisms obviously do? Are ecosystems alive only because their

[27] Referred to as *“Realizatioin”* in (Rosen, 1991b)

components are alive; or do they possess pre-organismic relationships (Chapter Two) that are perhaps not as rigidly defined? Relational theory allows both possibilities.

Defining Ecosystems and Ecoregions

National and international programs require ecological mapping as a geospatial science to support ecosystem assessments, monitoring, forecasting, and management. These needs are part of the current development of ecological informatics, which should provide information products and tools to track the accelerating changes in ecosystems; including species invasions, range shifts and other effects of climate change, human development and fragmentation, pollution, resource over-use, extinctions, disease vectors, land use and land cover change, and increasing societal demand for ecological goods and services (Chapter One).

Spatial concepts are fundamental to biogeography and can be traced to origins in "regional analysis" that date back to early traditions in geography (Forman, 1995). In ecology, spatial concepts were associated with the original concept of the ecosystem, introduced by Tansley ca 1935, with the concept of the ecotone, introduced by Hutchinson, and clearly reflected in the introduction of landscape ecology by Carl Troll (Troll, 1971). But of course, spatial concepts in ecology date to Charles Darwin, and before that were the subject of natural history and human ecology which began with the Greeks and came into focus in the mid 1600’s. The word “ecology” comes from the Greek root “oikos” which means “household.” Ecology in general did not receive much notice until the 1960's. (Krebs, 1985; Vink, 1983; Odum, 1953; MacIntosh, 1985). In all this time, however, little consensus was achieved on basic definitions (Peters, 1991; Whittaker, Levin, and Root, 1973; Grubb and Whittaker, 1989). Ecology seems at the end of this century in a similar state to that which Haeckel described at its beginning, where "*the problems of ecology are too complicated 'or not even susceptible to exact definition.'*" to allow rigorous science (MacIntosh, 1985). This situation leaves the definition of ecosystems and the geographic nature of ecological phenomena (and thus their mapping) without well-defined concepts, the result of which is a diversity of approaches that tend, through various logic, to emphasize highly selected aspects of ecosystems.

Terrell (1979) provides a glossary citing multiple definitions of the term "ecosystem." He states: "Some (Hanson, 1996) make a distinction between the two terms *ecosystem* and *biogeocoenosis* by using "biogeocoenosis" to refer to actual biological units (such as a certain bog) and "ecosystem" when referring to conceptual units. Others (Odum, 1953) make no such distinction." Terrell goes on to state a preference for "*Odum's lumping of the terms*" recognizing that *"in some technical, ecological literature the distinction is significant."* (Terrell, 1979) defines an ecosystem as: "*Any complex of living organisms taken together with all the other biotic and abiotic factors which affect them, that are mentally isolated for purposes of study.*" This suggests that ecosystem boundaries are mental constructions, whereas many studies take them as fixed eco-geographical entities (Bailey, 1976; Gallant et al., 1995; Omernik, 1995). Still others consider them ecologically determined and dynamic (Hoffman and Hargrove, 1999).

These needs also extend to human dimensions, where it is no longer possible to completely separate natural and human factors. The concept of regions in a traditional geography context is related to land use in a humanistic sense. Hart

(MacArthur, 1972) for example described regional geography as "*the skillful description of areas and places*" and "*the highest form of the geographer's art.*" In Hart's view, the region is equated with "*the land in all its moods and seasons*" along with "*the values, aspirations, and talents of the people who live on it.*" It is for this concept of a region that one can find music, art, and considerable pride; and it is not necessarily associated with any established political or other boundaries, nor can it be associated strictly with a race or culture, which may span many contiguous or non-contiguous regions or exist as enclaves within other more pronounced characteristics. The uniqueness of this kind of region stems solely from the relationship between people and their land, which is a functional and meaningful one. We may think of this as the human experience of our habitats. As such it is wholly tied to a deep concept of land use and human relationship with the land.

This particular usage is interesting precisely because of its artistic and not so scientific character. It has these qualities because it is an integrator of habitat and human function, and thus subject to the inherent uncertainties associated with human interests. We may think that a precise definition of regional boundaries in this case may be meaningless, but social/cultural regions are nevertheless discussed as though they were well known areas. Hart, for example, states that "*each region is distinctive*," yet there is little agreement on where they begin and end and one may be hard pressed to find even a hand drawn map in many regional studies texts; which rely instead on written descriptions of the regions character for such definition and approximate geographic transitions.

It is perhaps true also that the social/cultural region thus defined is as much a definition of what it is not, as what it is. In this sense, it is not a political, physical, biological, economic, etc. boundary that can be precisely defined, but a "distinctive" set of relationships that are presumed to cross such narrowly defined boundaries and depend instead on the subtle and sometimes emotional ties to the land that result from history—traditions and the memories of human effort expended in one area and in a given life style over time and generations. One can love this kind of region in a way that would probably not apply to a state, province, or county; an economic or social class; a physically defined area; or even one's own property. It is of this kind of region that songs and poems are written.

While it may seem thus a trivialization to attempt to map such regions, this may be quite necessary if there is to be a truly interdisciplinary science associated with land use. This, perhaps the hardest of all regions to quantify, may prove the most important with regard to human values which drive land use and affect other more rigid attributes. It may also be the most important from the standpoint of developing theory, for it is clearly the most abstract case of the functional unity; and who can claim that no other organism experiences its surroundings in such semantic ways, or that perhaps for all life there is not some common essence of this kind of relationship?

Accepting such subjectivities means, of course, that we might be mapping metaphors or even myths to some degree; but are they not also interesting and do they not at times change the landscape? The popular notion of "*the wild west*" in the United States may be an example. It is also clear that such regions could not be assumed to be unique for any given location -- these kinds of regions can freely overlap, and that overlap becomes a characteristic of a region. "Cathar Country" for example describes a region including the Catalonian district of Spain, Southeastern France and some adjacent areas. It refers mostly to historical traditions, the migration route of ancestral cultures, and the spread of religious beliefs. Catalonia is advancing today well into the forefront of modernity, creating strongly overlapping regional influences. To consider the extent and strength of these influences one should map their overlapping aspects and then develop models by which to evaluate general influences and trends. Bringing regional geography from art to science in this way would be no small task, but one with which spatial mapping and analysis could clearly help. With the new international agenda being outlined for land use and land cover change research, which will extend well into this century, these questions of regional definition will certainly gain importance, especially with the growing realization that land management must involve people ("stakeholders") at many levels and in all phases of management.

Another, more defined kind of region, is the political and economic region. These are regions defined by disciplinary analysis, not by the deeply human experience described above, but perhaps by deeply held belief. While more definable, they are in a sense less defining to the inhabitants except in extreme circumstances that invoke widespread effects or elicit strong feelings. Under everyday circumstances, the values in a political or economic region seem more transitory and less deeply rooted, though capable of great intensity (as during war). Economic zones, political boundaries, and supra-political regions fall into this category, which is widely discussed in political and economic texts (e.g., (Bradshaw, 1988; Keating and Jones, 1985; Bergman, G. Aaier, and F. Todtling, 1991) to mention a few). In the United States (Bradshaw, 1988) these socio-economic regions are "sub-national units of variable size" which "typically comprise parts or all of several states." They largely perform the same function but are less formal in the US than in Europe, where such regions may even be associated with a formal regional government authority (Keating and Jones, 1985) and take on much of the character of independent states, as in the regions of Spain (Kern, 1995). The function and character of this kind of region, whether strongly organized as in the European example, or loosely so in the US and other countries, is as a "physical, social, and economic unit for planning" and an "intermediate level at which intergovernmental differences can be negotiated and accommodated," and in the case of elected regional governments "relieving political and administrative overload." (Keating and Jones, 1985). This kind of region may perhaps have more to do with land management, conservation, and restoration practice than anything else, and than any of the other types of region; for this is the socio-political and economic action unit comprised from the bottom up of state agreements and from the top-down by sub-national coordination efforts. Again, even such highly abstract functional ‘forces’ distribute geographically and have effects on the landscape. If one looks at a satellite image of the border between the USA and Mexico the country boundary is clearly visible. This sharp difference began as a functional difference that was written onto the landscape over time, and that now is ‘read’ back into other ecological functions, in both the human system and the ecosystem.

In addition to the above examples, the concept of regions has been widely applied in other geographic disciplines. Kenneth Hewitt (Hewitt, 1997), for example, describes *"the geographicalness of disaster"* in a book titled "Regions of Risk." He states: *"Human geography records, especially, the various distinguishable habitats and cultural worlds, the places of shared existence around the globe."* This supports the idea of human habitat as a link between culture and land/environment, and mapping risks that result from that interaction. Hewitt describes danger as an intersection of four factors: hazards, vulnerability, context, and human response. A similar model used in ski instruction describes danger in terms of three factors: hazard, skill, and vulnerability; but clearly intervening factors of context could be added. Hewitt states that these four factors could be mapped independently and intersected to produce a map of present danger. Along with this idea he also suggests that the feeling of security, a socially causal factor, could also be mapped, especially following disasters: *"There is abundant evidence that people's attachment to place appears strongly in reactions to disaster and resistance to forcible removal."* Disasters that Hewitt believes can be treated geographically are: place annihilation, enforced displacement, ecocide, cultural annihilation, and genocide. This view seems to be yet one more aspect of the geography of the man-nature relationship, and one that should be included in an integrated concept of the "landscape" that includes human land use factors.

Nature and Man: The Paradigm of Landscape Ecology

Landscape ecology attempts to understand landscape "pattern and process" from an integrated perspective that combines both natural and human ecosystem factors active in a landscape (Forman, 1995; Turner and R.H. Gardner, 1991). This relatively new discipline borrows its concepts from many related fields, including ecology, biogeography, human geography and resource management and restoration fields. It is a natural combination of these disciplines, whereby "*the concern is not only with natural landscapes but with landscapes including man*" (Vink, 1983). With this convergence of natural and human sciences, new interdisciplinary uses and requirements for ecological maps have emerged, as evidenced by the now endemic use of Geographic Information Systems (GIS). The need for ecological mapping is also apparent in the currently rapid development of global ecosystem modeling (McKeown et al., 1996; Solomon and Shugart, 1993), and land use science (Walker and Steffen, 1997; Fresco et al., 1997; Turner II et al., 1995). It appears as well in new methodology associated with the development of an "ecosystems" perspective in resource management and planning (Renewable Natural Resources Foundation, 1996; Kineman and Parks, 1997; Kay, 1997). There is increasing interest in the United States, for example, to develop frameworks for integrated cross-agency ecosystem research (recent strategic plans) that may help approach certain very abstract concepts, such as ecosystem "health" and "sustainability;" concepts that tend otherwise to be defined only operationally. Correspondingly, there has been a recent rise in academic interest in system sciences, particularly the issue of *complexity* in nature and complexity of information (Kineman, 2003a). These trends are precipitating considerable debate of basic concepts.

As ecological and human factors affecting distributions and management designs become more intertwined, it becomes important to develop methods with a common theoretical basis. Modeling distributions with respect to habitat and environment is a rich area of current research in global and landscape ecology that requires a foundation to unify it. Many methods and models exist, and there is little methodological consensus among them and virtually no conceptual framework that ties them together or identifies which approach applies to what problem. O'Connor (O'Connor, 2002), in an introduction to a synthesis volume on species distribution modeling (Scott et al., 2002), bluntly criticized what he saw as *"a plethora of supposedly quantitative studies that cloud more than they illuminate."*

Theoretical Considerations

The relationship between ecological mapping, stratification, and niche theory is vague in the ecological literature. Conflicting views exist both in regard to the meaning of mapped ecological units and their appropriate construction. The issue is foundational and has everything to do with how a scientist chooses to analyze nature—the terms of the analysis. If we have a central theory—and here I consider the relational theory—then the units of analysis are determined. In a sense, they constitute a reduction because they are the building blocks of which we imagine nature to be comprised. If ecology does not have an agreed upon central theory, then there is pressure to adopt the units of traditional physical "reductionism," which, as explained in Chapter Two, is least suited for ecology. Alternatively we get a plethora of different units that each author considers instrumentally real. In the philosophy of science it is fairly clear that multiple kinds of theoretical reduction are possible and choosing the most useful one for a given purpose is at the very foundation of science.

But we have far more approaches than are warranted, and it is not too difficult to put them into a common framework.

The fundamental units of nature are defined in relational theory as *"functional components"* (Rosen, 1991b: 5F, pg. 120ff.). For example, we generally understand that to consider a forest ecosystem as primarily a physical unit might overlook certain meanings that many people defend quite strongly, from the functional to the spiritual. However this is not normally seen as a scientific loss if one adheres strictly to the physical theory. Relational theory recognizes functions that figure in the origin and definition of the system and its components—functions that may entail the system's stability. In short, it is possible to overlook the source of identity of an ecosystem; those properties that allow or prevent it from transforming into a different stability pattern. We are more familiar with the reaction of organisms to radical change in their contextual identity (life strategy and niche): they decompose if they cannot survive as defined. Ecosystem change can involve decay and functional change until there is a new stable condition where productivity can resume.

The fundamental unit of concern in relational theory, as described in Chapter Two, is the *functional component*, which is analyzed in terms of structure and function. This applies to ecosystems and ecological units but also can be applied to virtually any adaptive component from ecological to sociological and psychological (including functions that define identities, life and trophic strategies, ecosystem roles, and meanings[28]). From that perspective, useful conclusions about the role and meaning of explicit mappings of abstract functional relationships can be made. For

[28] These higher-level aspects of 'mind' are essential to consider at least for anthropogenic factors, which landscape ecology incorporates, but also in effect for all living entities. In relational theory, every system has a representation that is informational in nature, that is, an aspect of 'mind.'

example, one should abandon the expectation that explicit representations of ecological units are fundamental or stable (Hirzel et al., 2002). Ecosystems are not causally closed like organisms, enough or at all, to have well defined causal boundaries (which involve efficient and material boundaries). Most stable ecosystem boundaries are physically determined (as in a lake ecosystem bounded by the shore). An organism has sufficient 'semantic closure' (Mikulecky, 1999; Pattee, 1995) to retain some definition of self during adaptive and evolutionary processes. Relational theory identifies very special kinds of system closures that make up "Metabolism-Repair Systems" (Rosen, 1958a; Rosen, 1972), as responsible for the definition of organisms. Ecosystems have only semi-defined boundaries, as often debated regarding the nature of ecotones (Kolasa and Zalewski, 1995; Risser, 1993). All ecological maps should therefore be accepted as question-specific aspects of a system drawn from a complex definition of structure-function relations that allows many possible categories to exist simultaneously. They are thus quasi-natural and also open to human interpretation.

The expression of ecological units and identification of ecosystems is thus an issue in complexity, in sharp contrast to thinking of eco-units as defined structural components of a landscape and thus suited for rigid classification standards. Most national mapping programs seek standard classifications because of institutional, managerial, and political objectives. **Table IV-1** shows an eco-unit standard that was proposed for the United States. The units in the table were meant to be fixed geographic areas constituting a national eco-regions map (Bailey, 1976). Somehow we must supply that need from a more scientific view.

Planning / analysis scale	Ecological units	Purpose, objectives, and general use	General size range
Eco-region global continental Regional	Domain Division Province	Broad applicability for modeling and sampling. Large area planning and assessment. International planning.	1,000,000's to 10,000's of square miles
Subregion	Section Subsection	Strategic, multi-forest, statewide and multi-agency analysis and assessment	1,000's to 10's of square miles
Landscape	Landtype Association	Forest or area-wide planning, and watershed analysis.	1000's to 100's of acres.
Land Unit	Landtype Landtype Phase	Project and management area planning and analysis	100's to less than 10 acres.

Table IV-1: A Proposed US National Hierarchy of Eco-regions (Wirth, 1996)

If we recognize ecological units as constructed from functions (both human and natural), rather than as fixed objects on the landscape, emphasis can be more properly shifted toward relational definitions that underlie and interact with the patterns we may observe at any given time. These may include a wide variety of functions. Better yet we can develop methods for representing "functional clusters" that may allow models to be combined to reflect the concepts of ecosystem goods and services (Christian et al., 2005).

In one direction of relational entailment (environmental control) the structure of the environment and its geography places limits on an ecological distribution that are both physical and ecological. In this sense there is an aspect of ecosystems that is tangibly real and an aspect that is potential, acting like an attractor of future conditions. The analytical decomposition naturally leads to a concept of "ecological potential" which is then distinguishable from actual distribution and dynamics. Changes in that potential and associated response functions can explain certain kinds of dynamics that can be modeled iteratively and adaptively. The approach in general may help identify where other kinds of dynamics are important.

The traditional view of “pattern and process” when a relational theory of function is considered, translates better into *structure* and *function* (see Chapter Two). Relational theory represents these as complements in any view of nature. Here, “function” refers to the behaviors and roles a biological entity (or system) plays (or attempts) in a larger, context (the supervening system). Function can be inferred by experiment, whereas structure is measured. Their dependency on each other for existence is what makes a system ontologically complex, and if we do not wish to bury that complexity as a result of the units we choose for representation, we must represent both aspects. This complexity is often expressed in semantic terms, such as life strategies, goals, behavior, requirements, etc. Structure refers to the material states and interactions, flows, and exchanges that necessarily take place at a physical level. They are primarily biophysical, describing the mechanisms of the component system. The relationship between functions and structures is a complex one. Patterns and processes (which are both structural aspects of a system in the terms here) appear uncertain and exhibit non-linear changes precisely because they are entailed with abstract functions in nature.

Ecological Mapping Approaches

Ecological mapping includes the identification and delineation of both homogeneous and heterogeneous ecological distributions and their boundaries at all scales and all hierarchical levels. The goals of species-environment models (Heglund, 2002) include: prediction of species occurrence, distribution and abundance using habitat suitability, habitat capability, pattern recognition, and wildlife-habitat relations models. Heglund also notes the following spatial modeling techniques: expert opinion, correlation, ordination, gradient analysis, reciprocal averaging, multidimensional scaling, linear and nonlinear regression, and multivariate methods.

There are two basic approaches that can overlap in their purpose: (a) spatial ecological stratification methods as a means of dividing a landscape into meaningful units, and (b) ecological niche mapping as a means of predicting the distributions of functional components, including organisms and their functions, and hierarchically higher functional classifications.

Spatial stratification is a well-developed method in "design-based inference" that has been used for decades for ecological sampling and inventory (Norton-Griffiths, 1978; Jolly, 1981). Stratified sampling is statistically robust and has relevance across many disciplines. Its primary use has been for improving estimates of population or landscape level summary statistics; however, stratifying the landscape for specific purposes has more than transitory value. It is the foundation of GIS analysis of landscape issues and land management, and technically every environmental or ecological map is a spatial stratification. This is inherently an ecosystem approach to delineating eco-regions where various criteria for stratifying the landscape reflect perceived natural divisions. It more generally involves analytical techniques for defining quasi-real ecological boundaries from a complex set of extensively overlapping criteria.

Niche modeling and mapping, a fairly recent development (Liebold, 1995; Peterson, 2003; Levine et al., 2007), is a component-based approach to landscape ecology and biogeography. It is addressed by a range of methods, most of which aim at identifying "characteristics" of a distribution, but from highly diverse and often non-ecological (i.e., purely statistical) viewpoints. The organism-based, Hutchinsonian "n-dimensional niche concept" remains at the root of ecological thinking, despite surprisingly little that has been done with it in quantitative terms. It is generally agreed among ecologists that the fundamental unit of ecology is the organism (Huston, 2002) and that its most basic relationship with the environment is the ecological niche(Austin, 2002). Niche theory has also been extended to anthropological studies (Eighmy and Jacobsen, 1980) and in Landscape Ecology multiple ecological and human relationships are considered together. Accordingly, the fundamental unit of landscape ecology is really the niche, which expresses the system control of structural and functional relations. While niche analysis can be represented by a number of appropriately modified statistical techniques, these have not been adequately translated into a robust ecological theory, nor have they been integrated for routine use (Kent et al., 1997). Lack of ecological theory generally causes ecologists to defer to using methods from analogies in the physical sciences, analogies that relational theory would say are at least partly inappropriate. There are uniquely ecological considerations that can and should be added to drive technique development, and these needs should be communicated to the software engineers. Establishing sufficient theoretical agreement to make such recommendations has been extremely difficult.

Considerable confusion in the delineation of eco-units is evident in the diversity of terms used for their classification, as shown in **Table IV-2**.

Scale	**Areas**	**Borders & Transitions**
Global	Eco-region Domain and Division *(Bailey and Hogg, 1986; Bailey, 1996)*, Biome *(e.g. Pielou, 1979; Cox and P.D. Moore, 1980); (Solomon and Shugart, 1993); (Nielson, 1991)*Climatic Zones *(Cox and P.D. Moore, 1980)* Ecozone, Geozonal ecosystem *(Schultz, 1995)* Zonobiome *(Kent et al., 1997)* Life zones *(Prentice et al., 1992)* Realm, Region (Pielou, 1979) Realms *(Udvardy, 1975)*.	Boundaries (Bailey, 1998) Ecotones (Nielson, 1991)
Regional & continental	Eco-region, *(Gallant et al., 1995; Gallant et al., 1995; Gallant et al., 1995)*, Ecoregion and Ecodistrict (Klijn, Dewaal, and Voshaar, 1995), Regions (Gap Analysis Program, IGBP START program, sociological, political, and other geographic regions) Province *(Udvardy, 1975; Bailey and Hogg, 1986; Bailey, 1996; Pielou, 1979)* Human regions (Bradshaw, 1988)	Ecotone (Risser, 1993; Holland, Risser, and Naiman, 1991), Ecocline *(Kent et al., 1997),*(Holland, Risser, and Naiman, 1991), Transition area/zone (Holland, Risser, and Naiman, 1991) Boundaries (Botts and McCoy, 1993), (Choesin, 1997), (Kent et al., 1997), (Wiens, Crawford, and Gosz, 1985) Human Borders (Bradshaw, 1988)
Landscape	Ecological Land Units *(Klijn, Dewaal, and Voshaar, 1995; Smith and C. Carpenter, 1996)* Landscape Response Unit *(Haines-Young, Green, and Cousins, 1993), after Ramia)* Major Land Resource Areas (NRCS/USDA, 2006)	Landscape boundary *(Forman and M. Godron, 1981; Forman, 1995)*, Ecotone *(Clements, 1905) and (Livingston, 1903),* (Risser, 1995), (Matejka, 1992), (Kolasa and Zalewski, 1995), (Krall, 1994) Boundaries (Metzger and Muller, 1996) Zone of tension *(Kent et al., 1997)*
Community / assemblage	Community *(after Clements, Braun-Blanquet, and Daubenmire – (Odum, 1953)* Habitat & Habitat niche *(Odum, 1953)* Local ecosystem *(Forman, 1995)* Ecotope *(Europe and Russia; (Whittaker, Levin, and Root, 1973; Haines-Young, Green, and Cousins, 1993), after Zonneveld; (Klijn, Dewaal, and Voshaar, 1995)*, Biotope (Whittaker and Levin, 1977),	Range limits *(Trodd, 1996)* Edge *(Odum, 1953)* Ecotone (Kent et al., 1997)
Patch	Ecotope (see above) Biotope (see above) Mosaic (Forman and M. Godron, 1981; Forman, 1995) Patch *(White and Pickett, 1985)* Landscape Element *(Forman, 1995)*	Patch Boundary *(White and Pickett, 1985)* Ecotone and ecocline *(ibid)* Membrane *(Wiens, Crawford, and Gosz, 1985)*
Conceptual (any scale)	Ecosystem *(after Tansley),* Ecotone *(after Hutchinson),* Niche, Biocoenose, biogeocenose (see above) Habitat ((Clements and Shelford, 1939))	border, edge, borderland, transition zone, tension zone, marginal zone, zone of intermingling, zone of transgression, randzone, kampfelurtel, ubergangsgebiet (Kent et al., 1997)

Table IV-2: Terms for landscape ecological or biogeographical units

Table IV-3 shows the high degree of diversity and project-specific nature of eco-regionalization schemes and their respective stratification criteria. It is apparent that little commonality exists between definitions. This diversity emphasizes the need for a flexible method that can be adapted to different problem definitions and that can relate them to one another. While the concepts of human geography that Hewitt

Location	Units	Stratification criteria	Reference
	Actual		
Europe	Sub-national regions	administrative units	
general	landscape units	boundary complexity	(Metzger and Muller, 1996; Trodd, 1996)
Global	sectoral ecosystems	ecological land classification (ELC)	(Rowe, 1996)
Global	observed "world ecosystems:" classes	carbon content.	(Olson, Watts, and Allison, 1985)
global	major biomes of the African continent	Objective: cluster analysis of vegetation index phenology	(Gond, Fontes, and Loudjani, 1997)
Netherlands	Eco-regions and ecodistricts	subjective criteria	(Klijn, Dewaal, and Voshaar, 1995)
Nevada	Landscape Pattern Type (LPT)	dominant land cover types	(Wickham and Norton, 1994)
USA	hierarchical county-level eco-regions	discriminant analysis	(Olson, Watts, and Allison, 1985)
USA	gap analysis	biodiversity	(Scott et al., 1993)
USA	States and multi-state regions	administrative units	
USA and Global	1km land-cover classification	vegetation index phenology and multiple datasets	(Loveland et al., 1991)
USEPA	GAP analysis	Objective: vertebrate species richness	(Scott et al., 1993)
USSCS	Major Land Resource Areas (MLRA)	soil and terrain characteristics	(NRCS/USDA, 2006)
	Potential		
Australia	Vital Landscape Attributes (VLA) and Vital Ecosystem Attributes (VEA):	16 quantitative variables	(Aronson and Lefloch, 1996)
Canada	physiographic eco-regions	Subjective: Biogeoclimatic Ecosystem Classification (BEC)	(Newell and Bernert, 1996)
general	vegetation units	Terrestrial Vegetation Model (TVM)	(Leemans and Vandenborn, 1994)
Global	biomes	Simulated climatologies	(Claussen and Esch, 1994)
Global	Potential vegetation cover class	Physiography (climate, soils, elevation, etc.)	(Fedorova, Volkova, and Varlyguin, 1994), (Bailey and Hogg, 1986)
Global	Hierarchical	plant canopy structure &	(Running et al., 1995)

	vegetation classification	dynamics (from remote sensing refined by variables modeled from climate data)	
Global	global change	natural area protection	(Halpin, 1997)
global	eco-region biome boundary movement		(Neilson and Marks, 1994; Neilson, King, and Koerper, 1992; Neilson, King, and Koerper, 1992)
Global	ecozones of the world	bio-climate	(Schultz, 1995)
Global	Holdridge Life Zones	bio-climate	(Leemans, 1990)
Maui, Hawaii	climatic regions and zones	forest productivity	(Briggs and Lemin, 1992)
New-tropics	Eco-regional classification	malaria vector distribution and their environmental determinants (vegetation type, rainfall, temp. elevation, and geomorphology)	(Rubiopalis and Zimmerman, 1997)
Oregon	eco-regions	lacustrine ecology	
Slovakia	Territorial systems of ecological stability (TSES)	environmental management in Slovakia	(Topercer, 1995)
US Forest Service	bio-climatic eco-regions	Physiography (climate, soils, elevation, etc.)	(Bailey, 1996)
USA	landscape level (sub State) ecological regions	stream habitat classifications	(Bryce and Clarke, 1996)
USA	management areas	biodiversity	(Williams, 1996)
USA	management gaps	vegetation and vertebrate species distribution	(Scott et al., 1993)
USA	eco-regions	susceptibility to hazardous materials	(Burger, 1997)

Table IV-3: Criteria for Defining Units (stratification criteria)

described may well be mappable as landscape factors, they are at the same time highly subject to even daily changes in conditions as well as the viewpoint of the analyst.

One of the main difficulties that arise from the diverse methods for constructing eco-geographic maps is that, as a result, they are generally not very compatible with each other. They may involve complicated lineages that blur their definitions, and it is generally impossible to analyze error. The lack of a common experimental framework for their mapping thus prevents integration or meaningful comparison. For example, three different ecoregion maps are illustrated in **Figure IV-1**: Natural Landscape Types (Gerasimov and others, 1964), Ecoregions of the

Continents (Bailey, 1993; Bailey and Hogg, 1986), and World Vegetation Cover (Fedorova, Volkova, and Varlyguin, 1994). The first was produced as a paper map in an undocumented projection used at the USSR Academy of Sciences. It was one of the sources used by Bailey and very likely figured into the Fedorova et al. map. The extent to which its definitions carry into the other maps, and the error involved in reprojecting it by approximation techniques, is unknown. While each map clearly documents its own definitions, the logic for determining boundaries is lost in the art of translating from various sources defined differently. All three are primarily bio-climatic definitions, and yet there is no way to understand how their different regions might relate to each other. **Figure IV-2** shows a comparison between Fedorova et al.'s and Bailey's maps. **Figure IV-3** shows a comparison between Kuchler's Potential Natural Vegetation of the Conterminous United States (Kuchler, 1993; Kuchler, 1964) and Bailey's Ecoregions

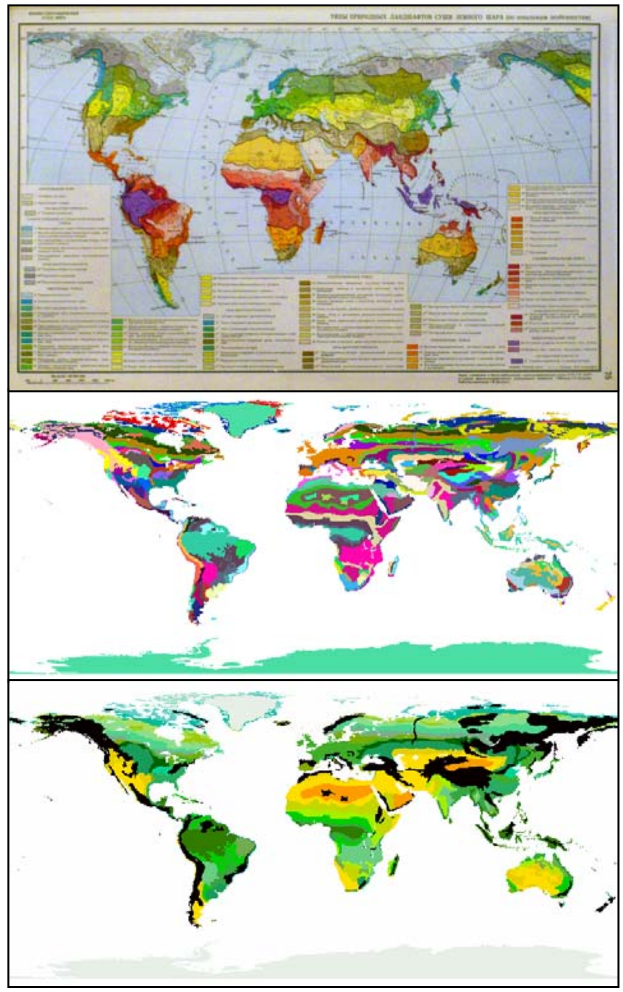


Figure IV-1: Ecoregion Comparison. (Top) Gerasimov et al. Natural Landscape Types. (Middle) Bailey's Ecoregions of the Continents. (Bottom) Fedorova et al. World Vegetation Cover of the Continents. Again, it would be extremely difficult to cross-reference any of these definitions or to analyze how their boundaries relate to each other.

Figure IV-4 shows a satellite image of "greenness" (Normalized Difference Vegetation Index) (Kineman and Hastings, 2000) with Bailey's ecoregions overlain. Again it is clear that the ecoregion boundaries do not agree will with an actual vegetation boundary (the general mismatch is about the same through the seasons as well). There are many factors that might figure into these differencs. Some explanations are:

1. The time of observation and/or of aggregation is different (seasonality has been averaged in all these maps, but information from different years and different annual ranges may have been used).
2. The satellite image shows actual conditions at a given time, whereas

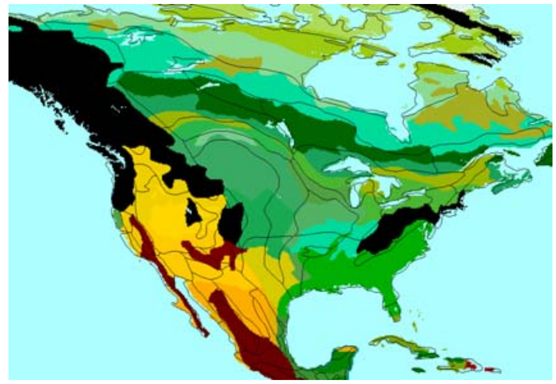


Figure IV-2: Fedorova et al. World Vegetation Cover (raster background) with Bailey's Ecoregions of the Continents (vector overlay).

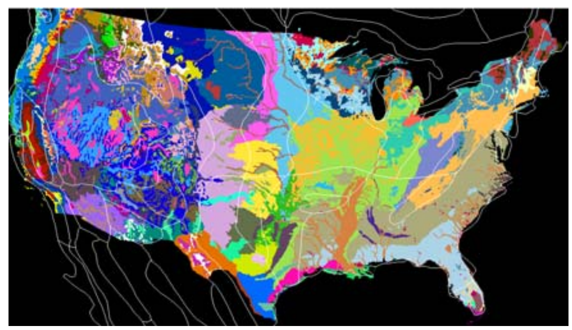


Figure IV-3: Kuchler vegetation units (raster background) with Bailey's Ecoregions of the Contenents (vector overlay)

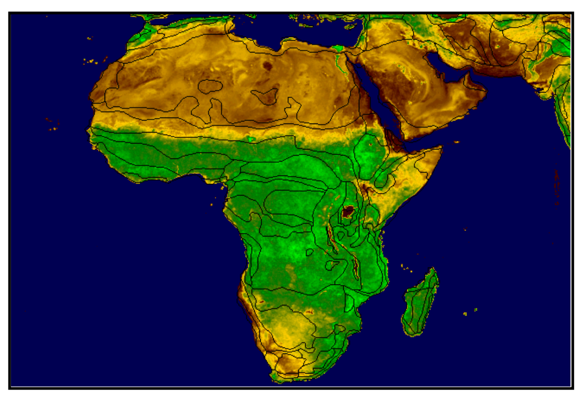


Figure IV-4: Greeness (NDVI) from Satellite with Bailey's ecoregions ecoregion definitions may involve theoretical potentials (actual vegetation combined with potential distribution based on climate data).

3. The maps contain unquantified mapping errors.
4. Definitions of ecoregions may differ. In fact all three maps depict different concepts of an ecoregion. The satellite image uses a color-slicing based on greenness, which is an indication of the presence of vegetation, mostly the vigor of vegetation (with some dependency on species, leaf type, leaf area, percent cover, growth stage and vigor, all of which affect the NDVI value).
5. Sampling and aggregation methods may differ. Differences typically exist in averaging method and what sample or averaging area the values refer to. These calculations are heavily dependent on scale and resolution or sampling density of the original data.
6. Different source data are used in each map. Remote sensing measures specific spectral signatures and classifies them, whereas the ground-based observations may include vastly different subjective categories. Proxy data may also be used.

The important question about these differences is whether or not they can be distinguished from each other. Only if they can will we approach a true science of ecoregions, for if the explanation of difference is arbitrary, then the differences are unexplainable. Approaches to this problem during the past 15 years have centered mostly on better documentation and metadata, which became formalized in the mid-90's in government and international metadata standards. However necessary this step may be—and it is extremely necessary—it is nevertheless incapable of changing a map that is essentially natural history, into a product that can be manipulated scientifically. It is clear that the vegetation boundary tracks simple bio-climate parameters, as at the sub-Sahelian border, much better than Bailey's bio-climate based ecoregions, and it is also clear that the difference is not explained floristically. I do not mean that such maps are not useful to science, as is all natural history information; but rather that the encoding process from nature to eco-region map is so inaccessible to later modification and testing that science cannot be applied to the mapping process itself. It is even the case that some ecologists believe it is quite right that such mappings should be subjectively derived specifically as expert opinions about the natural history (Omernik, 1995). A workshop was convened by the US Geological Survey to explore how objective and subjective methodologists might find common ground as natural history expertise is gradually being lost to more quantitative methods (Loveland and Merchant, 2004). Nevertheless, the problem remains unresolved.

The differences between ecoregion maps is thus only partly that of the scientist's classification scheme, which by itself would offer useful comparative information The classification differences, if they could be determined from the maps, represent complexity of the system that is important to analyze. Categorical definitions, which exist in both science and nature (being partly subjective and partly objective) have influences on the landscape. This is essentially an axiom of relational theory. The scientific definition attempts to identify distinctions that, aside from human interest, have natural meaning. Ecosystems consist of organic relationships that exhibit simultaneous and overlapping categorical properties that become entailed at the ecosystem level (see Chapter Two). Ecosystem identity (definition) and their boundaries are not stable like those of organisms because there is far less causal closure, if any. As a result ecosystems can change entirely without ‘dying,’ unless all the organisms die and none replace them. The patterns that ecosystems exhibit are dynamic, and complex, allowing ecosystems to overcome more physical limitations than organisms do, because they have the added advantage of being able to substitute different organisms to maintain various functions—the process of *functional replacement*. Ecosystem dynamics depend strongly on categorical aspects of their organization. The relationships between organism-based categories and the dynamics of an ecosystem can be analyzed using relational theory if a common theoretical and methodological basis were adopted for defining and mapping the categories. But without more standard mapping methods those complexities are muddled into a general uncertainty that tells us very little. We need an analytical mapping method so we can analyze the complexity.

As more automated methods appear on the scene it may be increasingly possible to separate many of the causes of difference listed above. However, this depends on how associated the automated technique is with ecological theory. It is possible to simply automate the process of producing natural histories without distinguishing the causes of difference. This is essentially what many statistical approaches do—they model the natural history, not the causal factors. As such they can be very accurate representations of that natural history, but very poor representations of ecological theory. Differences in distributions may thus be well documented, but differences in definition and the entailed factors may remain vague. If all such maps could be produced from a generalized niche model, as explored in

Chapter Three, it would then be possible to distinguish each source of difference. In this sense, we would enter into true scientific mapping, where theoretical relationships can be explored.

Figure IV-5 shows a climate cluster model (based on average temperature, rainfall, and cloudiness) overlain onto the Greenness satellite image, and it is evident that observation confirms a relatively simple climate model boundary much better than it does the corresponding boundary in any of the ecoregion maps. Why then, can we not produce the ecoregion maps from similar causal analysis? In fact this can be done using the niche modeling technique described in Chapter Three.

A map produced in this manner, based on presumed causal factors, states a number of hypotheses that can be tested by iterative sampling, where the initial map can be used to define sampling design. A transition from natural history maps to scientific maps involves just this kind of transition, where the attention shifts from obtaining a standard result, say for management or planning, to testing the theoretical relationships that underlie the mapping.

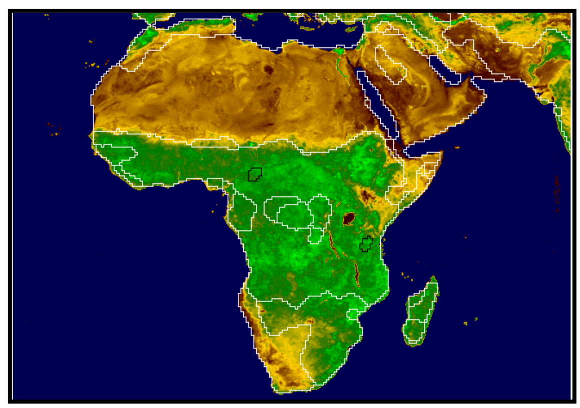


Figure IV-5: Greeness (NDVI) from Satellite with a climate cluster model.

Ecological Distribution Modeling

Scott et al. (Scott et al., 2002) cited progress and frustration in modeling species distributions with respect to habitat and the environment during 17 years since the “Wildlife 2000” synthesis (Verner, Morrison, and Ralph, 1986). Some of the challenges listed in the newer synthesis are summarized below:

- Improving the ecological meaning of models and avoiding over-application of statistical techniques at the expense of meaning (“*protecting the scientific community from spurious models*”) and ensuring “*validity of the underlying assumptions for the particular organism being modeled*.” (O'Connor, 2002).
- Recognizing organisms as “*the fundamental unit of ecology*,” and functionally significant causes and ecological principles such as the “*law of the minimum*” (Huston, 2002). There is an emerging consensus to view biotic distributions from the perspective of “*non-equilibrium spatial dynamics under habitat constraints*” (O'Connor, 2002).
- Defining the meaning of fundamental habitat relationships in terms of landscape ecological processes, spatial heterogeneity, and non-equilibrium; recognizing “*the importance of variation in time and space*,” and “*that almost everything we observe and model is sensitive to scale*.” (Wiens, 1994).
- Recognizing the ecological niche concept and individualistic distribution with respect to environmental variables as basic tenants for developing species distribution models. (Austin, 2002).
- Giving attention to appropriate interpretation of data types. (Huston, 2002)
- Integrating quantitative methods and expert knowledge. (Heglund, 2002)
- Using spatial statistics better. (Wiens, 1994)

In a thorough review of approaches for detecting and analyzing landscape boundaries (determination of “*landscape and plant community boundaries in* *biogeography*"), Kent concludes: *"The amount of literature of direct relevance is surprisingly small for such a potentially important aspect of ecological and biogeographical theory and this in itself provides a major justification for the call for further research on this topic."* He further stated, surprisingly, that many methods and techniques are available, *"but the most striking feature of the review is the limited extent to which any of these methods have been applied*." (Kent et al., 1997)

This temporary gap can be attributed to the lack of a clear framework for knowing how to apply the right techniques to various types of ecological problems. This has also left software developers without ecological guidance, resulting in a set of general capabilities designed primarily around physical and mathematical analogies. In fact, a range of solutions exist for delineating ecological units and their limits (Kent et al., 1997; Host et al., 1996; Haines-Young, Green, and Cousins, 1993; Johnston, 1978), but these must be better organized to allow software developers to respond with innovative and appropriate tools.

In a list of nine challenges for landscape ecology Risser (1987) suggests that available techniques developed for use in various disconnected disciplines should be adapted *"to more convergent and interdisciplinary needs."* This requires specifying the nature of the entities that might be mapped and their relationship to the larger body of ecological and geographic theory. Some authors have emphasized that the goal should be to not only describe patterns but to explain them in robust theoretical terms; to allow applied ecology to test theoretical ecology (Jordan III, M.E. Gilpin, and J.D. Aber, 1987). Unfortunately, it also involves significant controversies over approach, competing theory structures, and even the methods of science, greatly complicating analytical considerations. I believe it is possible to respond to these challenges only by developing an integrated modeling method (and corresponding software) reflecting the following design criteria.

1. Adopt a simple approach to ecological niche modeling that is intuitive (for the ecologist) and tied to basic niche theory and organism-based hierarchies.
2. Employ statistical tools in the estimation of model parameters, but allow ecologists to exercise judgment about their meaning.
3. Link analysis of habitat potentials with distribution dynamics in a useful way to reflect the modern view of landscape ecological dynamics within habitat constraints (O'Connor, 2002; Perry, 2002).
4. Provide a systemic methodology surrounding the modeling and mapping process to facilitate problem definition and to aid the ecologist in the application of appropriate techniques for a class of well-posed questions. “No amount of statistical modeling can compensate for a poorly defined problem” (O'Connor, 2002).
5. Provide for visualization and user interaction at appropriate points in the modeling process to ensure that intentions are being met and that ecological meanings are represented by the techniques being used.
6. Design the modeling and mapping process so that it can be applied iteratively, to converge on solutions, to modify models and data, and to test results. This recognizes that modeling is a process, not a product, and that outputs are hypotheses in an ongoing scientific enterprise that is intended to discover new

relationships in nature and represent them by modifying the model and its outputs.

7. Provide a scale-independent technique that can be applied to scale-dependent problems.
8. Provide a framework for these capabilities that is transferable between labs and applications, and that can reduce the production time for repetitive outputs. (Doering and Armijo, 1986), in a habitat evaluation for the US Forest Service, stated that: "*Developing HSI models was the single most time consuming task, requiring 28.6 working days to develop or modify 11 models*."
9. Link available GIS and modeling capabilities to ensure only necessary software development.

Although the terms in Table IV-2 would benefit from clarification, efforts at redefinition have generally failed to obtain consensus. As an example, the term "ecotope" is commonly used in Europe to refer to a "geographical extension of an ecosystem" at various scales, but is less restricted to a geographical definition in the United States. Klijn, et al. (Klijn, Dewaal, and Voshaar, 1995) prefers to rename this the Ecological Land Unit (Risser, 1993), and reserves use of "ecotope" only for relatively homogeneous ELUs. Whitaker, et al. (Whittaker, Levin, and Root, 1973) attempted to redefine "ecotope" non-spatially (a contradiction with the term "tope") as *"hierarchical 'place' in a set of levels in complexity defined by inclusive systems,"* but this was generally rejected (Grubb and Whittaker, 1989) Many of these terms are incommensurable without first establishing a better theoretical context. The effect is to render the scientific terms no more valuable than common ones. New definitions therefore cannot resolve the differences, but a focus on the theoretical context can clarify the use of existing terms and help relate them.

It should be clear from this analysis of regional concepts that no fixed categorical mapping of all possible regions would be feasible, because the criteria for defining regions vary with each application and question. Furthermore, finding any common classification basis for them would be equally unlikely—each reduces to its own set of ideas. We need a flexible method of mapping and a common theory of ecological entities. The relational theory can provide that, being broad enough to address diverse needs.

Conflicting Perspectives on Eco-Regionalization

Bernert et al. (Bernert et al., 1997) defines *"regionalization"* as *"the process of simplifying complex geographical phenomena into distinct areal units. These units are generalized and classified based on inherent properties."* The important question about this is if we imagine the process to be a prior analysis from which we derive reusable products or a real-time process by which we make classifications relevant to questions. E.C. Pielou states that: *"A perfect biogeographic classification of the terrestrial world is, of course, an unattainable ideal. Disagreements over the ranks to be assigned to the recognized units, and over the exact locations of their boundaries, are inevitable." (Pielou, 1979)*

Bryce and Clarke, discussing national to basin-level regionalization for research and management claim: "Regionalization is a form of spatial classification, where boundaries are drawn around areas that are relatively homogeneous in landscape characteristic.," They propose, for example, an eco-region classification "to bridge the gap between stream habitat and state-level eco-region classification (Bryce and Clarke, 1996)." They stated further that the purpose of regionalization at this scale is thus "to address issues of management at local scales…to aid in sampling design and extrapolations of site studies...in development of management practices more predictive of ecosystem response." Clearly these needs are problem-specific.

Klijn et al., argue in favor of quantitative and repeatable methods for delineating (and mapping) ecological regions (eco-regions or ecodistricts) stating: "*we should base the classification on characteristics that cause the pattern on the earth's surface, and not on characteristics that reflect it...*" and to use "*all characteristics that are ecologically relevant...,*" with a "*main requirement ...that their patterns should be easily recognized macroscopically, preferably even by remote sensing*" (Klijn, Dewaal, and Voshaar, 1995). Their concern was that "*many different geographical regionalizations were used in environmental research and policy, which was especially confusing for policy makers.*" Standards should therefore be applied to the theory and method, not the results.

An anatomy of approaches may help distinguish diverse needs among objective, quantitative, and subjective methods. In particular, one school of thought that was founded largely on the work of James Omernik (Loveland and Merchant, 2004), is that subjective approaches to delineating eco-regions are best, relying on a consensus of experts regarding what kinds of patterns should be considered and on what proxy basis they should be drawn (See, for example, Gallant et al., 1995; Omernik, 1987). The argument is that only from considerable experience does one gain an intuitive feel for the ecology of a place, sufficient to decide its appropriate ecological classifications, and that this is as much art as it is science. Gallant et al. (Gallant et al., 1995), for example, argue that subjective methods are preferable because they can incorporate the expertise of ecologists and draw on consensus views of how otherwise complex decisions about units should be made. Meanwhile, a number of authors have cited the advantages of developing systematic, repeatable methods for identifying ecological regions based on actual data (Bernert et al., 1997; Kolasa and Zalewski, 1995). This camp argues (Host et al., 1996; Schultz, 1995)that quantitative methods are required because they are objective, systematic, and repeatable, they can, for example, approach eco-regionalization with a rule-based process in a GIS employing standard classification methods, such as cluster analysis and other techniques.

There is a strong argument for establishing a permanent set of landscape units for "*organizing ecological information and management experience*" (Bernert et al., 1997). As we saw in Table IV-1, Wirth (Wirth et al., 1996) proposed a set of standard national eco-regions. Bailey recommends this approach in his book on *Ecosystem Geography, writing*: "*it is advantageous to have a basic framework consisting of a relatively few units to which all ecological land mappers can relate*" (Bailey, 1996). This is supported by Gallant et al. (Gallant et al., 1995), and is implied by Klijn et al. (Klijn, Dewaal, and Voshaar, 1995) in the development of eco-regions and ecodistricts in the Netherlands for "*communicating data on the state of the environment to policy makers.*"

Methods of regionalization can be further distinguished between those based on observed biological patterns (Bernert et al., 1994; Gallant et al., 1995) and those based on predictive variables (Host et al., 1996), thus delineating ecosystem "potentials;" and needs can be distinguished between those of scientific research and those of management and policy. **Table IV-4** shows a classification of diverse ecological mapping approaches in three dimensions: fixed versus flexible units; subjective versus objective determination criteria; and observed versus potential distribution

	A: subjective	**B: objective**
I: fixed	• geographical standard	• classification standard
II: flexible	• unique views	• multiple classifications

α - Actual

	A: subjective	**B: objective**
I - fixed	• common explanation	• common hypothesis
II - flexible	• unique explanation	• multiple hypotheses

β - Potential

Table IV-4: Classification of eco-region mapping approaches

An Integral Approach

While all eight categories in table IV-4 are needed for the different purposes reviewed above, the lower-right box, "Potential-flexible-objective," is of special importance with regard to implementing a common causal foundation. I believe that foundation can be based on a relationally complex approach in informatics by applying a generalize niche modeling method as described in Chapter Three.

Relational theory applied to ecological informatics suggests a key role for niche modeling in relating structure and function in two ways (Chapter Two). First, it can identify the environmental and geographic topology of any functions (which are direct expressions of some adaptive entity such as organism, species, ecosystem, human value, etc.) within a structural (environmental) context; and secondly such functional landscapes (or even function spaces comprised of multiple functional landscapes) can be similarly associated with possible new entities. Such alternative (unactualized) possibilities or optimalities for structures and functions may attract system development in indirect ways (selecting alternative structural and functional 'occupants'). This interpretation of functional (or structural) distributions, as "attractive" potential (Eighmy and Jacobsen, 1980) was demonstrated, for example, for wildlife "key ecological functions" in the Pacific Northwest (Marcot et al., 2002).

Implementing the complex relations described above requires a very general, theory-based approach (i.e., one where relationships can be tested). By employing flexible parametric mapping methods for these two kinds of relationship, we can meet criteria for "fixed" classifications simply by defining standard parameters of a "flexible" model for any standard map desired. Subjective determinations can easily be incorporated by adding subjectively determined causal layers—relying on expertise but with the advantage of being able to document one's reasoning as part of the layer definition. If the niche modeling approach is made general, to apply to all possible functional units or combinations of them, it can in theory meet the broadest possible array of requirements, bringing much needed consistency to the use of niche models in ecology and the social and anthropological sciences (Hardesty, 1972). For this to work, expert opinions need only be expressed in terms of maps of presumed causal factors. Even if an expert draws a line on a map from experience and intuition, it is possible to enter that as a mentally constructed criterion (Loveland and Merchant, 2004). The rough boundaries of "the old west," for example, can be produced from a variety of such criteria on environmental as well as social, political, and cultural distributions. Even vagueness itself can be expressed as an uncertainty value, appearing in the database and in the final product.

It is also possible to represent observed patterns or indicators of any actual feature on the landscape, modeled in a purely descriptive sense; that is, using variables that are not expected to be part of an adaptive relationship but only indicative of presence or absence. For example, a river may be taken as a river, not a potential river, and a model for its location may be derived from topography, location of riparian vegetation, or other surrogates (if data for the river are not available). Or the actual distribution of wildlife may be described using various indicators, proxies, or observations of their presence or absence. This case corresponds to the "Actual-flexible-objective" category in Table IV-4. There are a variety of classifiers and multi-criteria evaluators that operate in geographical space to accomplish this task, however it may be useful to include this case in the common framework so it can be entailed in the informatics with other distributions. The niche model approach can be used as a Case I application, as described in Chapter Three, constructing the hypervolume on multiple observational dimensions, for example different bands of multi-spectral imagery. In this case, the reflectances would be treated as indicators. While other, perhaps simpler, methods can be used, there is often a problem of data density and sampling where a niche model may be more useful for generalizing the observations. To use the niche modeling approach there should be adequate reason to believe the indicators will be modal, or will decompose in a modal analysis. Gaussian decomposition has been used in this way for spectral signatures (Sunshine et al., 1999).

Conclusion

Relational theory has potentially important implications for ecosystem and ecoregion geography. In particular it introduces a more general treatment of structure and function common methodological framework for integrating natural and human ecological analysis. Ecosystems, eco-regions, and eco-stratifications, as identifiable units, all share a common foundation in that they are functional components of a living system, comprising component or sub-system definitions of some kind with quasi-natural and quasi-arbitrary boundaries. Ecosystems are not organisms but they may exhibit collective organismic properties. They can have indefinite adaptive and evolutionary properties as a unit that exists somewhere between self-definition and human subjective determination. They are not mechanisms either, because they contain living organisms, which are not mechanisms; although they certainly embody many mechanistic components (i.e., components that lend themselves adequately to a mechanistic analysis). They are functional units in the sense that they identify a function or set of functions existing within some context. That context may be natural or human, or most likely both. They are complex systems consisting of living and non-living components. Accordingly, such systems and their complex components require a relational and functional analysis. The functions of such units may be like those of organisms or like those of mechanisms, or somewhere between. Therefore, to properly represent them in an informatics system, an approach should be used that is capable of integrating along a continuum between purely physical and purely organismic functions. That approach should easily accommodate socio-ecological units as well.

The extensive variety of mapping practice and requirements reviewed here lends considerable confidence to the exhaustive nature of the eight categories of mapping needs identified in Table IV-4. A conclusion of this study is that the relational theory discussed in Chapter Two, and entailment of structure-function relations via a suitably generalized niche modeling procedure, as described in Chapter Three, can be used to meet the requirements of all eight categories. That approach is capable of providing the necessary framework for the definition and mapping of ecoregions and functional component distributions in environmental and geographic space.

To bring stratification methods into the relational architecture suggested in Chapter Three would require definition of each eco-unit to be mapped as a separate ecosystem component. Clustering methods could be used to produce the unit definitions. The final ecoregion map would then be produced by combining the distributions of each unit, assigning the greater suitability. An option would then also exist for defining ecotones. While simple approaches to ecological stratification for sampling designs and other purposes certainly retain their place, it should nevertheless be possible to produce equivalent delineations from niche-based relational informatics. While standard methods have the advantage of methodological ease and readily available software tools, results may be difficult to integrate with the relational architecture. The relational architecture, if constructed, will offer advantages in better definition the units and their overlapping areas, scientific testing, and further application of the ecoregion units in query and modeling functions supported by the general architecture. A further advantage of the relational architecture would be the ability to relate eco-unit maps to each other, and to functional groups.

The case of mapping potential distributions engages a fully complex model in which distributions are established on the basis of both dependent and independent variables affording additional possibilities of complex analysis. The case of mapping actual distributions is a simplified case of the more complex method that, nevertheless, benefits from generalization by providing a means for interpolation across areas of missing data. This, for example, can be important in classifying satellite imagery where certain pixels may have bad values.

Chapter Five:

Impacts of Relational Ecological Informatics

Scientific, Political, and Ethical Implications

Abstract

Application of relational complexity theory to ecological informatics offers a means to meet the information needs of society for ecosystem science and management, and to improve scientific communication generally. The goal of ecological informatics is to establish communication between science and society; however, our common way of structuring information according to physical concepts of nature does not adequately inform us about complex living systems. Relational informatics provides a more appropriate theoretical foundation and empirical basis for representing complex living systems structurally and functionally. Information constructed on physical-mechanistic premises fragments "facts" from their contextual meanings. For complex systems this is an irretrievable loss. The effect of this loss on society is to allow arbitrary contexts to be applied instead; fueling conflict, polarization, and misinterpretation of "the facts." Application of relational complexity theory to complex informatics may offer some hope for resolving this problem. The implications of relational theory are thus far reaching across many dimensions of human society and management of our natural world. By providing a more complete concept of information itself, relational informatics should be more capable of effective communication between science, policy, and ethics as three fully entailed components of Man's relationship with nature. Implicit in that relationship is a new

understanding of nature and humanity as a integrated whole, sharing both intrinsic and instrumental values. Relational informatics suggests a deep integral framework for information that may improve our understanding the relationships between nature and human society in scientific, political, and ethical dimensions. The underlying assumptions of relational complexity are found to be consistent with a typically Eastern world view, where the origin of reality is both universal and intrinsic (Brahman and Atman). A major result of this study is the discovery that typically Eastern and Western thinking, which represent intrinsic vs. instrumental value beliefs respectively, are two parts of a whole that may be re-assembled by the framework of relational theory.

Introduction

I have shown elsewhere that a new information-relational view of nature as a complex system that models itself—relational complexity—is theoretically general to mechanistic concepts of nature (Chapter Two). I have also shown that this relational view can be translated into an effective epistemology of living and complex systems based on empirical representation of structural, functional, and contextual information (Chapters Two and Three). In Chapter Four, I described some impacts this theory could have on landscape ecology, providing better definitions of ecosystems and regions, and allowing to present diversity of land classification methods to be unified. There are other implications of this theory in ecology (Kineman, 2007), evolution (Kineman, 2002), and cosmology (Kineman and Kineman, 2000; Kineman, 2000). Here I will discuss implications for environmental science, policy and ethics.

//Current approaches to environmental informatics are generally unable to meet the needs of ecosystem management because they do not effectively *communicate* to science, society, and policy sectors. A recent study (by the author) attributed this failing to a physical science bias in the history of environmental data and informatics, and consequent dominance of physical concepts of data and mechanistic definitions of information (Chapter One). While this is not an argument against observational data, it is an argument that these data on their own are too incomplete to communicate natural meanings that could genuinely inform society. A more complete view of information in nature and informatics can be achieved by collecting system-specific information about ecological *functions* (Chapter Two). An approach for doing this can be derived from relational complexity theory, after Robert Rosen (Rosen, 1978; Rosen, 1985a; Rosen, 1991b; Rosen, 1999). It is possible to develop *Relational Informatics* by expanding present informatics that are predominantly structural (i.e., syntactic) to include function (i.e., semantic) information elements and relationships that are necessary to capture and express the underlying complexity of a living system (Chapters Two and Three; Kineman, 2007; Kineman, Banathy, and Rosen, 2007).

Relational Informatics, in terms of Rosen's relational theory, views nature itself as an information system involving a complex communication that makes itself empirically evident through ***structure*** and ***function*** (Rosen, 1971; Rosen, 1973) These terms are defined as information relations by which nature models (i.e., represents) itself; they are the encodings and decodings of Rosen's *modeling relation* (Chapter Two). Rosen described the structure-function relation as *"an entirely objective* *description"* of a natural system, structure being "*what it is*" in an observational or interactional context, and function being "*what it does*" or might do as a specification of change in a given system (Rosen, 1973; Rosen, 1971). This definition expands the normal usage of these terms in ecology; which has been restricted (Hochstrasser and Yao, 2003), because of the tendency to 'physicalize' the idea of *function* (as in the idea of mechanical process). Rosen's theory provides a general ontology in category-theoretic terms, from which both mechanical and living systems emerge.

Figure V-1 shows that the Structure-Function dichotomy as embedded in the ontology of Rosen's modeling relation between Natural Systems and Formal Systems. *Function* can be understood here to refer to that which in nature or in information systems induces or specifies change detectible in measures of a system. *Structure* then refers to the aspect of a system that can be fully described by spatial and temporal measures.[29] An important and controversial aspect of the relational ontology is that its information entailments describe and thus reify the basic *mind-body duality* implied throughout philosophy, science, and culture. This is precisely what makes it appropriate for describing living and social systems and, it turns out, complex systems in general. Even physical systems are a special case where natural Law substitutes for *mind* (Kineman, 2003a). Relational theory in these

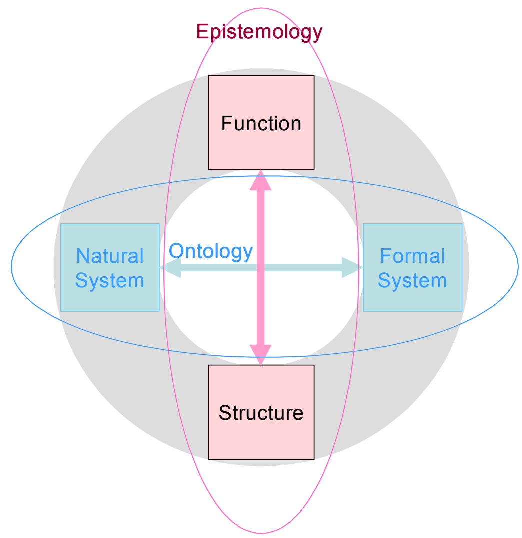


Figure V-1: Structure-function epistemology emerges from relational ontology

[29] This does not necessarily correspond with common usage in ecology. For example, *trophic structure* involves both structure and function. In relational terms it would be more precisely called *trophic organization*.

terms is general enough to represent all kinds of natural phenomena, from physical to psychological and cultural/ethical/spiritual, and to allow one to model how such phenomena may interact in a given system (see Chapter Three). Mechanistic theory, in contrast, fragments this relationship, relegating all aspects of *mind* to either humans or natural Law and all actual systems in nature to machines. It is thus incapable of dealing with complex phenomena involving natural information relations in which laws are system dependent. In a manner of thinking, such relations suggest that we consider *mind in nature,* e.g., (Bateson, 1979). As I will discuss, this general viewpoint is what allows the approach to integrate information across scientific and humanistic perspectives.

There are problems, however, with objectifying the mind-body relation in this manner. The main issue, and why it was not permitted in traditional physics, is that it allows a model to contain *closed causal loops* (e.g., A causes B and B causes A a-temporally). We must then impose an arbitrary sequence in order to compute such relationships by iterative approximation. Before such computation, however, the ontological assumptions can be preserved—in other words the informatics can reflect the ontological conditions of a Rosen modeling relation if it is allowed to contain loop entailments; however accessing its information will then require some form of arbitrary questioning or sequencing of events. In theory, simulations can be done this way, reducing the sequence step as much as performance and data will allow, to better approximate a natural condition. If this is done, in theory the essence of natural complexity will be retained in the approximation, which can then be made arbitrarily more meaningful by addition of similar relations. It should be equally clear from this description that the mechanical limitations of present computers prevents us from achieving a truly complex informatics architecture aside from human inputs, but it can be a system by which we access aspects of that complexity.

The *closure* of certain causes within a system, particularly an organism, has been associated with the uniqueness and definition of life (Rosen, 1991b; Pattee, 1995; Schrödinger, 1943). Such closures (which correspond to mathematical *impredicativities)* imply self-constructing and thus self-defining systems. The tremendous success of mechanistic theory, *for describing mechanisms*, was precisely a result of discarding these loops from analysis, because they are fully reduced to equalities in mechanisms. However, Rosen and a number of others argued that such loop causalities are precisely what characterize life and all truly complex systems. Other forms of computational complexity, Rosen argued, describe only complicated mechanisms and thus cannot adequately represent life. Rosen thus urged that we "*abandon the equation of objectivity with mechanism*" and "*allow an objective status to* [relational] *complexity*"; in other words to, "*objectify impredicative loops*" (Rosen, 1993). It turns out that direct and indirect entailment of functions with their material referents (structure) is how that objectivity can be achieved. Ulanowicz also provided a strong case for loop causalities defining living systems outside the confines of mechanism (Ulanowicz, 1997).

These ideas run contrary to most of our training in Western science. Ecologists, however, have already broken the taboos of mechanistic theory often, out of the necessity of their field, but except for the brave they have done so reluctantly, apologetically, and not rigorously. The successful examples became legendary, such as L.S.B. Leakey's radical departure in primatology to spawn the study of social relations of great apes from the *inside-out;* that is, by entering into functional relationships with nature rather than trying to observe them with classical independence (van Lawick-Goodall, 1971). Another obvious exception to the mechanistic taboo that occurs in ecology is inescapable reference to system-dependent ecological functions in terms of *life strategies*. Such concepts have had to be kept at some distance from the field of evolution which holds as tightly as possible to mechanistic formulations. A brief exploration of the implications of relational theory in evolution (Kineman and Kineman, 1999; Kineman, 2002) suggested that there should be no epistemological or theoretical conflict; however these conclusions go against certain established dogmas that adhere to the limitations of physical/mechanical determinism. One such dogma is the idea that every course that nature takes, which we can observe historically, is the only course that it could have taken, given initial conditions. That mechanistic restriction does not apply to the analysis of complex systems. It is then impossible to impose a deterministic history on evolution. If we could understand that the mechanistic limitations were imposed on theory in order to better study only one special class of systems—the non-complex—then ecology and evolution could unify and establish a theoretical basis on a par with physics (as often hoped), and in fact more general to it. This is a conclusion that Rosen emphasized many times in his work. In Rosen's words:

> *"...in order to be in a position to say what life IS, we must... understand... what life is NOT. Thus, I will be spending a great deal of time with mechanisms and machines, ultimately to reject them [as explanations of life], and replace them with something else. This is in fact the most radical step I shall take, because for the past three centuries, ideas of mechanism and machine have constituted the very essence of the adjective "scientific".... It makes the question "What is*

life?" unanswerable; the initial presupposition that we are dealing with, with mechanism, already excludes most of what we need to arrive at an answer. No amount of refinement or subtlety within the world of mechanism can avail; once we are in that world, what we need is already gone. Thus we must retreat to an earlier epistemological stage, before the assumptions that characterize mechanisms have been made." (Rosen, 1991b: pg. xvi)

He reassures us, however, that: *"In this approach, mechanism does not disappear, it becomes a limiting case of complexity"* (Rosen, 1993). From Rosen's perspective, the relational view is completely general to the mechanistic; that is, the mechanistic view can be derived from natural relationships, but not the reverse. For no amount of general (physical) causation can fully explain behavior resulting from system-dependent (living) causation. It is unquestionably a more general theory, but the real question for science, if there remains any doubt, is about whether or not system-dependent causes truly exist. The mechanist's commitment is to the idea that they do not; that any appearance of such will eventually be reducible to mechanism. But for the ecologist, or anyone who wishes to have a theory to apply to life today, the assumption must be made that such causes do exist. Nothing could be more important in the advancement of natural science, policy, and ethics than to develop just such an integral perspective that allows theoretical consideration of both kinds of causality. We may be reminded of Gregory Bateson's comment on the mechanistic view (to which he referred as "Cartesian dualism"):

"If I am right, the whole of our thinking about what we are and what other people are has got to be restructured. ... The most important task today is…to learn to think in the new way."... "It is doubtful whether a species having both an advanced technology and this strange way of looking at the world can endure" (Bateson, 1972*)*

It turns out to be quite easy to correct our thinking and science/informatics designs; we must consider system-dependent laws alongside the general ones. These appear in relational theory, and in the ecologist's vocabulary, as natural "*functions*" that are as unique to each living system as its structure, and that drive its organization and behavior. In other words, there does not appear to be a universal set of functions (Platonic laws) to which all living functions can be reduced, as one finds in mechanisms. In that case, if system-specific functions are not recorded, they are lost in the analysis and irrecoverable later. Rosen concludes his 1993 paper by saying, "*In such a complex world, functional descriptions are perfectly meaningful, and can be quite independent of any mechanistic ones.*" (Rosen, 1993) We see also that function, as both meaning and potential, is not a mere artifact of human thought—it has a place in nature and comes out of nature. Difficult as it may be for many scientists to accept, this enters us into the world of *2^nd^ order cybernetics* where certain forms of teleology and vital concepts become necessary.

These ideas will underlie the discussion that follows of *communication* in natural, human, and cognitive systems, and their integration. The point will be to project the likely effect of relational informatics on communication between science, policy, and ethics, and the possible effect of more complete communication resulting from it, on these domains.

Improving Communication

Given the above, it should be understandable that present day science and informatics do not communicate well with policy when it comes to questions about living systems. This problem has been debated for some time. For example, *(Hammond and Adelman, 1976)* wrote:

"For their part, scientists are uncertain whether their contributions should be restricted to presenting the facts, thereby leaving the policy judgment entirely to the political decision-makers, or whether they should also advise politicians which course the scientist believes to be best. And politicians, for their part, are uncertain how much scientific information they are supposed to absorb, and how much dependence they should place on scientists for the guidance in reaching a judgment about policy. As a result, the scientific community continues its seemingly endless debate about the role of science and scientists in the body politic."

These are not the appropriate choices, however, when one considers that scientific judgment can and should be expressed in the science, regarding the meaning of facts in original and analogous contexts. These authors go on to state: *"The key element, therefore, in the process of integrating social values and scientific facts is human judgment..."* Nevertheless, separating syntax and semantics from their original context—not capturing meaningful aspects of natural behavior captured alongside the facts—places unrealistic demands on human interpretation and judgment later, fueling controversy instead of resolving it. The root of the problem is thus in the quality of scientific information itself, its incompleteness when taken in the traditional sense as a body of "facts," as most information systems do.

This conclusion is supported by the observation that policy and science connect best within well-established 'hard' disciplines, where the functional background is solidly established in natural law and taught from grade school through college. But in contrast, policy communicates to 'soft' science, not the reverse, to select from or create an obliging diversity of facts that can be matched to a given premise (Sarewitz, 2000). The problem is again clear; the natural semantics for interpreting facts have not been universally established, nor are they communicated with the facts, allowing such post-hoc 'cherry picking.' This procedure seems characteristic of today's environmental discourse (Pielke and Sarewitz, 2003). A mechanistic formulation of information strips away natural context and meaning, and consequently allows human-applied context and meaning to be substituted. The lack of original context (which supplies the natural meaning of the phenomena) tends to drive environmental decisions and supposed ethics toward pure social construction, in which science and other forms of original knowledge (experience, intuition, and introspection) are devalued or ignored altogether.

The inadequacy of present environmental informatics seems revealed in the fact that, with few exceptions, it does not entail the unique functions of living systems, but requires them to be added later, after they have been disconnected from observations and generally lost. The process goes unnoticed because of our general material outlook, in which we do not appreciate this loss of meaning because we are used to material laws, for which meanings *are* general and *can* be added later without any loss. This perspective works to support political and personal objectives, and increased polarization of society (Sunstein, 2002) as we are forced to entertain arbitrary and often unrealistic semantics. Current attempts to address this problem reflect the dream of a "semantic Web" that will add meanings to data:

> *I have a dream for the Web...Machines become capable of analyzing all the data on the Web – the content, links, and transactions between people and computers. A "Semantic Web," which should make this possible, has yet to emerge, but when it does, the day-to-day mechanisms of trade, bureaucracy, and our daily lives will be handled by machines talking to machines...(Berners-Lee, 1999).*

As these ideas have evolved, there have been are a number of interesting and promising technologies. "Latent semantic analysis" (Landauer and Dumais, 1997; Edmonds, 2001) is a technique in computational complexity ("microworld") research that *"starts with creating a matrix of actions by trial"* and infers meaning from mutual encodings with other systems and contexts (Quesada, Kintsch, and Gomez, 2001; Edmonds, 2001) Similar ideas are begin developed for education and outreach, for example in "Recommender" systems for orienting museum visitors according to their own semantic profiles (Aroyo et al., 2007). "Global Agoras" based on "Webscope" software for democratic collaboration (Christakis and Bausch, 2006), and other socially constructive facilitation technologies, are aimed at evoking or building new semantic contexts, tapping, perhaps, the reaches of the human mind.

Nevertheless, these approaches necessarily presume that the meanings they will add either exist in some form and can be accessed with appropriate technology, or that they can be constructed or evoked from the subjective mind with appropriate methods. They further assume that a language can exist in which this matching can be generally accomplished. Even Berners-Lee, while remaining optimistic, now recognizes that this vision is not materializing as imagined (Shadbolt, Berners-Lee, and Hall, 2006), mostly being plagued by the problem of standards. It thus leads predictably down a mechanistic path, seeking as Hilbert did (see Chapter Two), a standard formalization that will cover the intended domain. When that domain is complex, the terms of reference themselves must be allowed to change and that may easily result in a standards gridlock that can only be resolved by higher supervening semantic systems, also requiring standards, and so on. The problem is that standards are syntactic and semantics cannot be replaced with syntax without incurring an infinite regression. As a common joke goes, *"I love standards; there are so many to choose from."* Many things can and are being done in this field to associate facts with new meanings despite the limitations of that exercise due to competing standards; however far more can be achieved if the information base is reconstructed on relational principles from the ground up.

Of greatest concern here is the loss of original meaning in scientific communications due to an information concept and architecture that is impoverished and in need of repair from the very start. Original meanings cannot be re-attached to data after the two have been divorced, one existing in a database and the other “out there” in the human knowledge-scape. The presumption that such imagined synthesis can be an inverse equivalent of a prior analysis is incorrect. It is thus no surprise that the greatest success of the World Wide Web was its early use in the physics community, where semantics is better established, outside the Web, than in many other fields. However, it is true that by imploring new meanings from new contexts, a very interesting and creative world can be formed; this cannot recover a lost empiricism about natural relationships.

The Web contextualizes, but while inventing new frameworks that may continue to diverge. Relational theory may challenge the basic assumptions about the Semantic Web; stating a principle that original semantics that were lost during initial data storage and transmission, can never be recovered properly. The danger to society, then, is that we may become lost in our own constructed realities and lose sight of more extensively evolved realities in nature. The lessons of such self-indulgence are all too clear from history.

I do not wish, however, to be tied to a bleak forecast; there is a possible convergence where Web development can unite with integral content generation and management, combining their benefits. This is the vision I have for the future of informatics, but to date in environmental informatics, integral content production and management in complex fields (including ecological), have received far less attention than applications where the original fragmentation of data from behavior can survive post-hoc integration, delivery, and semantic interpretation. As we march down this path applying it to everything, however, we leave the comprehension of living and social systems, farther behind.

There are, of course, examples on the Web of ‘whole’ information resources where content remains integral between syntax and semantics from a credible origin. Accounts from human history probably serve as a good example, where they come from original records where both facts and their meanings were recorded in a real-time context, in human language and art forms that we can relate to. Art is another example, where structure and function, technique and meaning, must be integral and usually complex. Complex in this case does imply that it may have many interpretations, but nevertheless the existence of a work of art is the existence of a meaningful communication from a source; not simply a catalyst for constructed meaning ad hoc. Medicine is perhaps another example, where we intuitively know to look for in vivo reports and testimonies that give us not just the facts and statistics about a drug, but also the human stories; or where experiential procedures are combined with data and actual trial results for training. In as similar way, a visual, or perhaps interactive, natural history of a rain forest conveys far more natural, original meaning than a database, and yet the database gives us tools for management. Somehow, these fragmented elements of communication must be combined at the source. There is nothing preventing such development in science, and I will refrain from speculating on whether or not natural selection can draw this out where needed. It seems that the potential is there, except for certain traditions that may be hard to break.

I also do not wish to place Rosen's relational view in opposition to that of Berners-Lee; they are not really opposed to each other, they just address different aspects of complexity. In relational theory, as I have described in previous chapters, it is possible, even natural, for many contexts to exist simultaneously or to be created over time, and also to be constructed from subjective processes. Indeed this was the model for how nature itself is to be explained in this view. The many additional contexts that can establish new meaning and that are constructed (or objectified from the subjective) are essential ingredients that relational informatics would be capable of representing. My argument has been that the picture is out of balance and such added semantics in fact dominate in present technological society, having significant effect on human action and the environment. While I have argued for the importance of retaining the original semantics, it is precisely these added contexts that they must be combined with if we are to effectively manage "ecosystem-management" rather than allowing it to take a purely relativist course. But that does not exhaust the challenge.

Ecosystem management requires knowledge of the original natural context, the ecosystem and the organism as they actually have lived and do live. It is not a matter of post-hoc re-construction. The original natural contexts must be represented. We can represent natural contextual relations in terms of system-dependent functions, keeping track of where they came from. In other words, Artificial Intelligence in a Semantic Web cannot replace an original empirical context. Efforts to standardize metadata attempt to preserve some aspects of original context, but far more is needed to capture knowledge about natural functions in terms of models, descriptions, and even analogies.

For example, many biological information systems constructed today consist substantially of object and location/time (aside from collection and project metadata), the most basic physical parameters that can be recorded about its existence, begging even the simplest knowledge of ecological functions other than *presence* (i.e., an existence function). This assessment applies not just to species databases, but also to ecosystem, eco-region and eco-unit descriptions which are a broader taxonomy similarly objectified. Many such descriptions are geographical rather than eco-geographical, making them appear to be fixed units. Such approaches are very far from current need to represent ecosystem dynamics, let alone services, which, are the functions we wish to manage (Christian et al., 2005). Beyond that are natural values, which can also be represented as functions of nature and society (Kineman, 2005).

Two-Way Communication

Relational theory represents two-way rather than one-way communication. In other words, it is incorrect in relational theory to think that some*thing* we call *information* 'transmits' from one point to another. Information in relational theory is a property of systems *inter*action, with emphasis on the two-way relationship, also described in a modeling relation. Just as information relations in nature are proposed as the drivers (functions) that produce or explain change, so they can be in human communication, if the natural completeness of information can be retained in the informatics.

Figure V-2 shows a compartmentalized "end-to-end" concept of information based on a natural communication between four elements of an informatics enterprise. This model of informatics has been presented in national and international program plans for building comprehensive environmental and ecological informatics. A very similar four-part framework was also presented to the US Congress by intelligence experts arguing for better national security informatics (Steinberg, 2003). Each compartment is an identifiable stage in developing information for practical use, and these four basic components appear to be valid for informatics needs in general. They are each whole activities that are equally informed from either end; in other words, as we saw in Chapter Two, true information requires a two-way transmission, without which there is only data transmission, open to variable interpretations. We

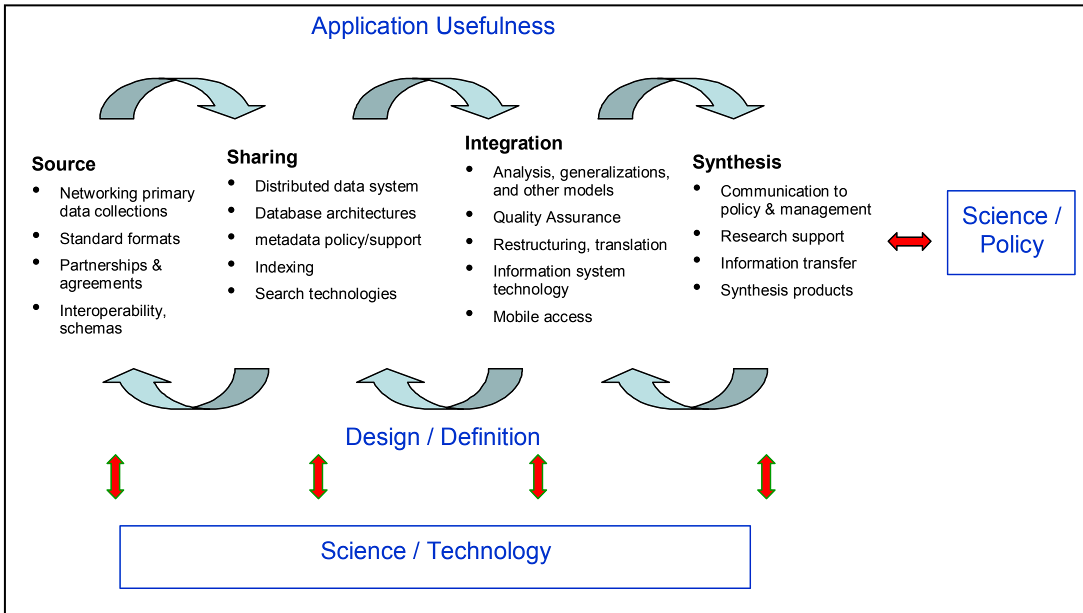


Figure V-2: Holarchy of Four Critical Compartments of Informatics have assumed a linear transfer of data that is somehow translated into information which, through decision making and experience becomes knowledge, and which finally informs policy. However, this chain is currently broken and none of these categories effectively build on the former because there is insufficient coupling between them to communicate semantic content. At the end of the process only a true expert can bring in a sense of natural reality (the original semantics) from prior experience with it; but in today's skeptical, pragmatic, and socially relative society experts are trusted no more than anyone else who can write or speak well.

Today's environmental data systems tend to focus primarily on the first two stages, *Source* and *Sharing*, leaving the rest for scientists and policy analysts to do. The entire end-to-end process is rarely managed by one group. As a result, these compartments are not usually connected very well with each other. As I have pointed out, this can be acceptable in regard to physical/material information where meanings are fairly general (for example, a minerals database) and can be re-supplied at any stage. But fragmentation of the diagram destroys meaningful communication with regard to complex and living systems. To effectively communicate on any given policy or scientific issue, the relations between these four components must be preserved in order to communicate meaningfully; as indicated by the encoding and decoding arrows in the diagram (application vs. design). This concept is also compatible with the idea of "iterative design" developed for managing complex organizations (Girajadigi, 1999). We can see that where the problem of communicating useful information has been taken most seriously—the case of national security—strong recommendations have been made, and very large budgets proposed, to formalize and manage the entire end-to-end process.

Integration of environmental/ecological information is often discussed today, and there have been many experimental integration efforts involving remote sensing, spatial analysis, in-situ, and data mining technology in, for example, studies of landscape ecology, climate change, conservation ecology, biodiversity assessment, and many emerging areas of ecosystem management, the newest paradigm in government environmental policy. Methods are highly variable and attempts to formalize integration facilities have generally failed (e.g., the multi-agency Terrestrial Ecosystems Regional Research and Analysis Laboratory – TERRA Lab, which existed in the early 90's in Ft. Collins). Without well-established efforts for general integration of the functions in Figure V-2 (above), information for synthesis and for communication with all sectors of society is not available, forcing assessment programs such as the recent Millennium Ecosystem Assessment (Millennium Ecosystem Assessment Board, 2005) to rely on prior reports and the general literature. Since the work being cited comes from different contexts, employs different methods, and asks different questions, the strength of conclusions can remain weak (Ashbindu Singh, UNEP, personal communication). Attempts at better organization of integration and synthesis efforts for ecosystem information exist (such as forecasts of agricultural weather, drought, disease vectors, red tides, and various climate change impacts) and these are notable in their pioneering efforts; however operationalizing and validating products from such work has been difficult, owing to the difficulty on the one hand of defining and prioritizing problems requiring information products, and on the other to the lack of a standard approach to preparing such products and using them to inform the decision process.

Ecological characterization (EC) was developed by pioneering work in the 1970's (Johnston, 1978) as a way to meet urgent needs to inform decision making about ecological choices. It has been revived recently in digital form with more modern approaches to data presentation (Kineman and Parks, 1996). EC was one attempt to get at the functional aspect of ecosystems, by performing an in-depth synthesis by site to complement broad ecological generalizations represented in local, regional and national databases. The need to more explicitly address ecological function for decision making has been a recurring theme in ecological monitoring programs such as LTER (Hochstrasser and Yao, 2003). In 2005 an explicitly functional framework for coastal ecosystem monitoring was proposed by the Ecosystems Working Group[30] of the Coastal Global Terrestrial Observing System (CGTOS) Implementation Team, which was unanimously endorsed as a central component of the proposed system (Christian et al., 2005). Similar recommendations (unpublished) were made to other large-scale informatics enterprises that were being constructed at the time (for example, the Pacific Region Integrated Data Enterprise (PRIDE) in 2005 (Diamond, 2006), the Integrated Ocean Observing System (IOOS) (National Ocean Partnership Program (NOPP), 2006), and implementation of the US Node (OBIS-USA) of the Ocean Biodiversity Information System (Grassle et al., 2005)). Nevertheless, support remains poor for these efforts. Representation of biological species remains poor in general, and virtually none of the major information systems incorporate explicit information on biological or ecological

[30] Chaired by the author

functions. A successful effort was made to include "Key Ecological Functions" related to organisms and ecosystems for wildlife management in the American and Canadian Pacific Northwest (Marcot and Vander Heyden, 2001). Again, such pioneering efforts have not been well understood (Bruce Marcot, personal communication, September, 2007), and hence not widely adopted. Ecologists generally agree that a functional approach to understanding ecosystems and biodiversity is essential, but theoretical and methodological progress is needed along with a much better general understanding of living systems and how their informatics requirements differ from what we are used to.

The reason for poor integration of ecological informatics within its own boundaries, as well as with environmental informatics, should be obvious by now—we have constructed informatics according to a picture of nature that is appropriate for physical systems but not appropriate for living systems. The first two compartments in **Figure V-2** can be separated from the last two in informatics about physical systems, because in that case, and only that case, integration and synthesis can be de-centralized, having well established general semantics. In other words, the appropriate meanings can be added back in the integration and synthesis stages from knowledge of general functions (the physical laws). For this reason, one-way data/information transmission models work much better for physical systems, even those with considerable uncertainties, such as weather forecasting systems. The analogous concept of "ecological forecasting," however, does not have an analogous methodology. It instead requires more complex information that effectively retains the means for functional interpretation at each stage.

To properly describe living systems, including psychological, social and societal systems, feedback of information from the end of the process to the beginning is as necessary as the feed forward of information. For ecological informatics, each compartment of Figure V-2 derives part of its definition through feedbacks from the other levels. These connections exist not just hierarchically, but holarchically; in other words they can bridge levels. *Synthesis,* for example, may precede *Source* data collection and define its requirements—the very essence of scientific design. Iterative convergence on management solutions may also be essential, as emphasized in "adaptive management" (Holling, 1978). Hypotheses about management effect belong in the *Synthesis* compartment, whereas their testing reverts back to the source of information and engages the entire communication holarchy. If different theoretical contexts exist in these two components, the connection is lost. Similarly, *integration* should be conducted not just on available resources, but in full relationship to questions and needs. These seemingly obvious principles can be applied in a more piecewise or socially fragmented manner for physical systems, adding up the results later. However, for the reasons of relationship mentioned above, applying ecological information to societal problems requires a very high degree of linkage across all four compartments, and a more complete concept of information. Implicitly, all four levels require equal support and development if we want ecosystem information to inform social priorities. Better methods for relating these components are needed also if we are to consider the linkages between ecosystems, human systems, and value systems.

Unity of Communication

Natural science, the science or art of policy and decision making, and ethical philosophy should form an inter-communicating unity. This seems implicit in the goals of scientific and social institutions through traditionally anticipated benefits of science for society, ideals that policy and decision making appeal to or promote, and principles of good behavior that are or become embodied in public law and religion. With regard to the environment, while most people and cultures expect to have the right to use resources, they generally have a sense of ethics regarding that use. These norms become codified in constitutions, laws, religious codes, and everyday conversation. In other words, most societies have a sense of what is good, aspire to it when they feel it is possible, and attempt to implement it in their actions. This sometimes takes exception to and sometimes harmonizes with the perceived necessities of life in an apparently competitive world. The term *informatics* implicitly involves the idea that effective communication and useful information should somehow improve how we conduct human affairs and how we achieve our goals.

If we accept this premise, then it stands to reason that there should be some aspect of science, policy, and ethics that can at least relate them to each other and allow them to communicate effectively. While there may not be agreement on which goals or values are good or appropriate in a given circumstance, there may be general acceptance that goals, beliefs, and actions should be connected for progress to be made and that some process of information is involved in connecting them. Even a strong belief in diversity and competition requires a self-consistent and generally accepted program to maintain and communicate those principles in society, as can be seen in most capitalistic democracies. Some form of social, political, scientific, and ethical unity, through communication, might thus be stated as a generally shared value.

This concept of shared value is diagrammed in **Figure V-3,** in which a more whole scientific information base is depicted as capable of responding to, and providing realistic alternatives for policy analysis and decision making. Such policy, properly informed, can mediate between ethical beliefs and natural philosophy. We can even discuss the relationship between science and ethics, in this view. Ethical values may be seen as *socially constructed* or *acquired* from nature. But perhaps more important than how we view their acquisition is how we view their origin. As the view of 'Man as separate from nature' has emerged from history, there has arisen a corresponding split in basic beliefs about the reality of values and ethics. <insert explanation> These two options have defined a great philosophical debate about the division between humanity and nature associated with many well-known dichotomies: industrial society vs. traditional cultures, East vs. West, North vs. South, "have" vs. "have not," Man vs. nature, nature vs. nurture, and ultimately mind vs.

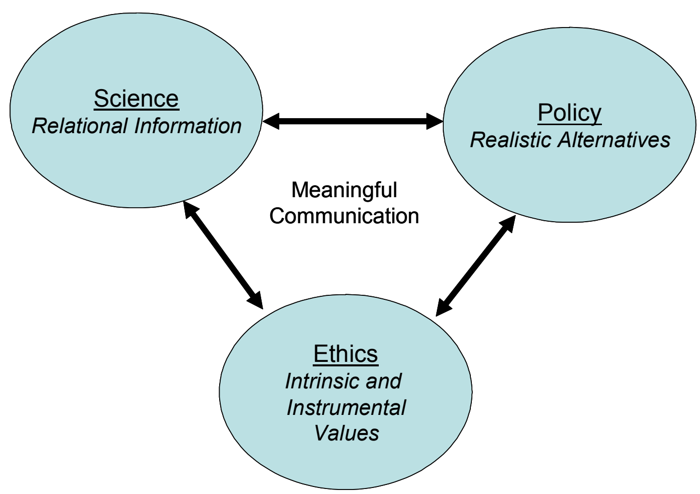


Figure V-3: Communication Between Science, Policy, and Ethics body, as mentioned earlier. To an important degree it also defines the division between natural (scientific) and spiritual (theistic) knowledge, with each side claiming that the other is not knowledge. As if not to be outdone, nature itself has revealed a dichotomy between existence (which we must presume) and knowledge (which we can experience) that prevents us from peeking behind the curtain—the "epistemic cut" referred to earlier. All of these differences may be seen as "duality," which appears in every manner of thought—or they may be seen more usefully as *complementarities* described by a modeling relation. In this way, relational theory and informatics may help us approach the *non-dual*.

We thus have a means for repairing our fractured unity, or resolving dualism through relationship. We should not assume that the task is unapproachable, or that appropriate methods do not exist. In fact, if we are not aiming in this direction the entire discourse of social responsibility seems hollow. Science may have aspired to autonomy from social forces, but as the famous philosopher of science, Thomas Kuhn, came to realize, it has never achieved it, nor would that be healthy (Kuhn, 1970). Even Karl Popper, later in life, converted to the belief that "metaphysical research programs" are an integral part of science, evaluating and reforming its underlying assumptions (Popper, 1965). The relationships in Figure V-3 between science, policy and ethics are therefore legitimate ones, about which a science or scholarship can exist. This contrasts with views of science as an independent body of knowledge, views of policy as entirely new social constructions, and views of ethics as personal inventions or tradition for tradition's sake. Instead we may find that relational principles can be used as a tool for exploring the balance and integration of these domains. Uncertainty about the next step that such thinking can take—beyond duality and mechanism—fuels countless claims of "the new science" or "the new paradigm." These are not to be trivialized, but it is clear that they have not yet acquired anything approaching the unifying foundation that relational theory can provide.

Informing Science, Management, and Policy

For much of the history of environmental management we have assumed that the mismatch between science and decision making is a matter of the amount of data. Data enterprises emphasize quantitative content of science and information products and quantitative measures of progress at the expense of relational meaning.[31] We can see this clearly in national "performance measures" for ecosystem management, such as "the percentage of ecosystems with improved ecosystem health." [32] The fallacy, of course, is that neither *ecosystem* nor *improvement* can be uniquely quantified, nor can *health* be adequately defined without a means to reference the functions that it comprises. Inappropriate quantitative and deterministic measures are often forced into the goals of major global science programs because of the general mind-set that meaning and measurement are the same thing, when, as I have argued, they are complementary opposites. It was once popular, for example, to state to Congress and the general public that the goal of climate science is to *"reduce uncertainties in climate models"* (McCarthy et al., 2001). It is hard to argue with this from a mechanistic outlook, but it falsely presumes that the accuracy of prediction can be

[31] *Meaning* is used literally here, in its relational definition, as *role in context*. This is not meant to imply that numbers cannot be meaningful, if, as Bateson said, they refer to "a difference that makes a difference" (Bateson, 1972).
[32] Quoted from NOAA Strategic Plan, 2002

improved indefinitely, whereas for complex systems it cannot. Establishing a belief that infinite improvement is precise knowledge is possible can result in delaying decisions based on current knowledge. Also if we miss the point that uncertainty is an irreducible and *necessary* characteristic of these systems at some level, failure at prediction may tend to discredit the entire enterprise. A more realistic concept is *ecological forecasting*, which recognizes that a science of complex systems can only draw reasonable boundaries on the future. This idea should be more popular with politicians when it is understood, because it also implies that policy and decision making are the proper domains where uncertainty can actually be reduced, at least in the short term, if science properly informs them. A better understanding of complex behavior can give substance to the idea of *precaution* (in terms of reducing uncertainty and risk), which otherwise may draw warranted criticism for being too vague and open to political interpretation (Pielke, 2002).

To the extent that decisions are rooted in known system principles, and not clouded by the false perception of prediction or simplistic measures of success, desired value outcomes might be sustained longer. To the extent that we have a system in which the characteristic effect of decisions can be evaluated in realistic scenarios and simulations, the idea of a responsible, precautionary decision can be recovered. The same relational informatics proposed, which is adaptive, can be used to track the effects of decisions so that action can be constantly corrected, further reducing risk.

In the relational view described here, the causal action of information within a natural system is the very source of complexity. That view can equally describe the nature of science and management; in fact, Rosen's modeling relation was originally developed as a meta-model of science. It follows that as we create information systems and enterprises that are used for management, we actually *add* complexity to the system. For that addition to result in risk reduction we must have a better grasp of complexity; otherwise our incomplete knowledge may make the future more uncertain, not less. We need an informatics system, therefore, that can discover the latent potentials of a system, explore the uncertainties, and present reasonable scenarios of how it might develop under different conditions and decisions. This can support decision making by presenting reasonable, science-based and value-based alternatives. A primary goal of environmental and ecological informatics should then be to provide a robust natural reference system for assessing future scenarios.

It is important to realize that the discrepancy between scientific models and nature is not merely a matter of accuracy. Complex systems express characteristics of surprise and non-linear behaviors that inherently cannot be calculated in advance. Because science, policy, and ethics are becoming increasingly related (whether our practice of them reflects this or not), our ideas themselves can induce unexpected results in the natural world. The value, therefore, of a relational theory and informatics design, which can deal with both natural and human complexities in an integral framework, should be immense. To begin with, it allows us to see natural and human complexities as an integral whole, and thus to examine their relationships in some depth.

Implications for Social Priorities

The main components of Figure V-1 (earlier) were analyzed by Banathy as four primary areas of science and management that should receive balanced attention and funding priority. The lobed region in the center of **Figure V-4** represents the domain where we can *directly* and even mechanistically relate knowledge of the elements in the diagram. It also represents the degree to which we can target effort and resources. Outside this domain we can imagine that the elements are related *indirectly*, in more complex ways involving natural selection and system attractors that cannot be directly managed.[33] Inside the lobed region is what we can measure and manage, outside is what we can only infer or intuit; an important point being that there is such a boundary. Here, the limits of precise knowledge are clear. In the vertical axis the boundary is a practical one—we can collect only so much data and infer only so many functions with given resources. In the horizontal axis the boundary is an epistemological one—there are uncertainties in applying inferences from past behavior to the future, and we must employ tools of uncertainty, including reasoning by analogy and function, and general principles (rather than general laws) that seem to apply broadly. In essence we move from a precise knowledge of natural systems to the possibility of *wisdom* about them. Accordingly, wisdom practices and their terms

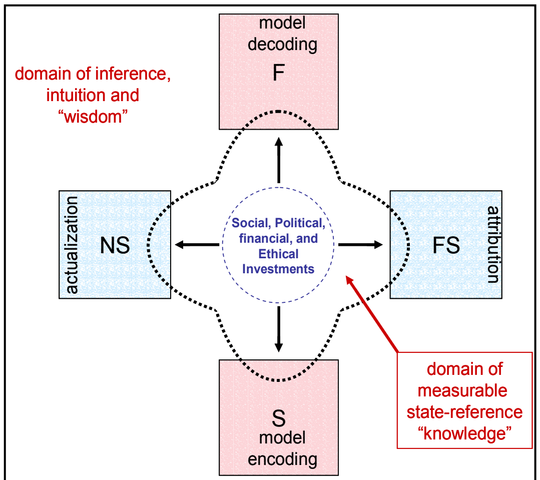


Figure V-4: Balancing Human Investments

[33] These direct and indirect relations, described in previous work cited, are shown in Figure 1.

of reference should become part of this science, and not turned out by a false ethic of precision or measurability.

The recommended emphasis on monitoring both *structure* and *function* requires designing and building the corresponding information systems (Chapter Three). It also involves funding field or lab work to collect data and to determine functions as they exist in context, and how these functions are related to environment and biological sub-components (including organisms). Practical involvement requires equally balanced attention in terms of ecosystem management as a *formal system* plan and monitoring program (as in Hollings' adaptive management monitoring protocol), and hands-on management practice that exists in the *natural system* element of Figure V-1 (earlier). Banathy used this diagram to emphasize the need to partition tasks between human beings and computer-based processes, to engage with natural complexity through computational and intuitional faculties using the appropriate system (computer vs. human) for each. Banathy wrote:

> *"The unintended consequences of a failure to achieve appropriate task partitioning may be devastating, particularly with respect to scientific models applied to management of natural resources and ecosystems."* (Kineman, Banathy, and Rosen, 2007).

He also notes the importance of maintaining this balance in outreach, education, and the development of ecological ethics banathy.

Transcending Ecological Conflict

Many scientists believe we are facing an ecological crisis (Chapter One) that demands the equivalent of efforts being deployed in the name of national security, but with regard to ecological threats (Pirages and DeGeest, 2003). Conflict over natural resources is recognized by NATO, the United Nations, the World Resources Institute, and many other organizations, as an important factor in global conflict (NATO, 2005; Myers, 1993), perhaps rivaling or combining with ideological conflicts in the near future, due to climate change and its interaction with human designs. In this sense, even if we were not to consider climate change as anthropogenically caused (as some still debate), its effect, nevertheless, is highly conditioned by the human landscape and social systems. In other words, metaphorically, it is not necessary to say that Man influenced the ocean in order to know where responsibility lies when a house is washed into the sea. The real question is what we are going to do about it.

Unfortunately, there is a tendency to seek compensation rather than resolution of the problem, and this generally is done through competitive means. Conflict over natural resources has historically been a factor in war, and it need not have anything to do with the causes of change, only the distribution of their effects. Even ideological or holy wars may, at root, have more of a utilitarian foundation than is commonly recognized. If major changes in the Earth's climate continue, and societies continue to compartmentalize space and resources, it is predictable that ecological changes will shift the suitabilities of landscapes for traditional uses, displacing people and governments, and sending them searching for new territory or control of distant resources. More borders are defined today than in history, and a significant proportion of our natural resource base is fragmented into geographic regions that do not allow movement. This seems likely to prevent both the natural and human world from accommodating change smoothly.

It appears that those human sectors that will see the greatest impacts from climate change are, in general, the lesser-developed countries in locations with already threatened resources, situated in vulnerable areas, or with fewer options for mitigation (Solomon et al., 2007). The assessments also imply that disproportionately large impacts from the industrialized world may cause feedbacks in terms of ecological, economic, and political turmoil. These effects may not be proportional to their causes and may arrive as sudden and surprising change. Such predictions cannot today be made reliably, but it may be possible to understand a great deal more of how complex systems behave through relational analysis; for example developing tools for "forecasting by analogy" (Glantz, 1988; Glantz, 1996).

Although the debate will continue over how much change is caused by human alteration and dominance of natural systems, it is nevertheless reliably reported that these things are happening, and human response is, in any case, needed. UNEP's Global Environmental Outlook (GEO-3) considered four options for decision making: "*Markets First*" (the global economy decides), "*Security First*" (isolationism, protectionism, and disparity decide), "*Policy First*" (government decides), or "*Sustainability First*" (a scientific or ethical principle decides) (UNEP, 2002). Arguments about ecosystem health and human well-being can easily be dwarfed by market and security perspectives which are more tangible and rewarding to sectors of society that may hold power. We will no longer accept, in the modern world, decisions based on moral and ethical values that are dictated, regardless of their basis. In this sense we are becoming less culturally conditioned and at the same time increasing the emphasis on personal psychology. Meanwhile, we seem to have retained traditional economic and security motives that are easier to define and agree on than general ethics, because they excite primal fears. These motives, unfortunately, lead to further conflict if they do not factor in a broader perspective. The combination of personal doubt about ethics and value, with personal certainty about economic and security fears is very dangerous. There is no counter-balance to control the spin of fanciful solutions.

If relational theory and informatics can provide a tool for balancing and integrating these sectors in a more comprehensive way (than the Millennium Assessment proposed to do, for example, with ecological spreadsheets), it may begin to dissolve some of the extremely dangerous polarities that exist today. What cannot be imposed as an ethic may nevertheless be found to emerge from a different kind of natural analysis, becoming both personal and general at the same time. Personal belief need not be derived from authority, but from understanding of the method by which natural functions were studied and the principles thus derived. This is in fact the main reason we believe in physics. Even good predictions do not inspire belief in the person who made the prediction; we believe in the discovered principle, the natural function. For example, if ecologists have established through many studies that mountain lions will switch their feeding habits to prey on humans under certain conditions, this is powerful information that can help us manage human-lion interactions and prevent a problem. But if we only have reports of unfortunate incidents, fear will generate all kinds of explanations, eventually calling for complete destruction of the menace. This is not an uncommon scenario in farming and ranching communities, and it applies equally well to global environmental issues. I believe we have entered an era where individuals can no longer the agents for transferring the needed information about ecological function, simply because they are no longer trusted. It may then seem lame to suggest that instead, an information system would be trusted, but informatics is a social enterprise at the root of science, not just an information system. By establishing an ethic and practice from recording functions as they are studied, a body of testable knowledge can become established. Just as it would be political suicide to challenge the laws in most physics text books, it could become equally problematic to go against a well-established functional informatics enterprise that is not the sole product of any political, scientific, religious, or other faction of society. A collective pool of knowledge about ecological function can provide the boundaries for what is reasonable to say about ecosystems; boundaries that do not seem to exist today in public discourse.

Most US resource science and management agencies now state an environmental policy of *sustainability* while other portions of government deny the very existence of ecosystems as manageable entities (Fitzsimmons, 1999)[34] This may seem astonishingly ignorant of systems in general (consider, for example, analogy with the presumed reality of an economic system). But this is a symptom of the inability of systems science to communicate, resulting in an inability of culture to develop a broad understanding or means to deal with even the most basic concepts of complex living systems. Oversimplification passes for wisdom in this void. But in any case, to the extent that ecosystem science and informatics appear uncertain and open to interpretation from any perspective, they do not connect with human desires nearly so well as a set of syntactic rules that promise at least some certainties. And in

[34] Fitzsimmons was appointed to head the US Program for Wildfire Protection

a culture focused on rule-based management, concern for ecology can be easily dismissed, even made to look weak or naive, because it is unruly (or even unlawful, perhaps, to the physical scientist). Quantitative accounting of short-term goods rather than qualitative understanding of long-term values prevents political and economic interests from perceiving any gain in return for investments in ecosystem assessment and management. The result of investment in uncertain long-term strategies, from a business perspective, is unwanted control, like a mechanical governor on a powerful engine that limits its output and, if not adjusted right, will cause the engine to go into cyclical spasms. In the short term, systemic feedbacks do not equalize everyone's benefits, and thus the forces for individual gain at another's expense will drive the system if there is no counter process to ensure the common interest.

The complex nature of ecosystems is clearly at the root of *problems,* in a policy-analytic sense (Clark, 2002), that demand decisions to reduce uncertainties or chart a desired direction through them. The apparently positive step of accepting ecosystem management language in policy and program planning may, in part, be the result of integration of ecological economics into the policy discourse, thus providing it with more tangible and familiar terms. But these terms are inadequate, nature having far more than one form of currency to which it might be reduced; and thus it cannot be reduced without losing most of its value. Ecological communication is thus still limited by the lack of diversity of semantic elements. It is otherwise a curious fact of modern culture that physical *things* seem more legitimate than systemic potentials or principles: "sustainability" is politically weak compared to "goods and services." But de-emphasis of the relational erodes the system concept itself. The word *ecosystem* is often left out of discussions of *environment* and *society*, when it should be obvious that ecosystems are what bind them. *Environment* is incorrectly imagined to include ecosystems (which are thus highly reduced in concept); but to the ecologist, as a matter of definition and axiom, the term *ecosystem* rigorously includes the environment without diminishing its complexity or importance. The ecosystem is logically the more inclusive domain, but this appears as a paradox to the physical scientist.

The physical perspective is one based on discrete difference, whereas the ecological perspective is one based on discrete relationship. Only the relational view can integrate both perspectives. The aim of communication might thus be stated as conflict resolution in the broadest terms, where we move from a *fractional* view of nature to a relational view. We cannot claim that the relational view is a view of the whole, however. It is a view of relationships that, in an analytical sense, unify wholes. We thus retain Korzybski's admonition that *"the map is not the territory"* (Korzybski, 1933) and even formalize that idea, while still making a better map.

Nature and Humanity in Relationship

Mankind seems to strive for some form of harmony or unity on many levels while attempting to resolve, survive, or transcend conflict. The idea that this may be a natural urge, in the sense of Tielhard de Chardin's "Omega Point" (Teilhard de Chardin, 1959) or Hermann Hesse's "Glass Bead Game" (Hesse et al., 1969), correlates with the relational view of nature discussed here. For when one builds a comprehensive theory of relationship, one cannot avoid projecting an ultimate *whole*, just in the same way that a mechanistic formulation of reality projects ultimate fragmentation as a singularity at its origin (and perhaps end). Such projections are a logical consequence of the separation of pre-ordained or prior "natural" laws from the natural systems they describe. Ineffable *life* or *soul* then must enter or inexplicably emerge from a living organism as in Descartes' mind-body dualism (Descartes, Miller, and Miller, 1644), or as the philosopher Gilbert Ryle critically put it, *"the ghost in the machine"* (Ryle, 1949). Descartes' view described a separated reality that is perceptible to the senses—a reality based on differences, while the alternative is to describe inferred relations that unify the perceptions into wholes, both relative and absolute, that are interrelated. Bateson echoed Ryle's critique of Descartes' "category error" by identifying difference with perception (Bateson, 1979; Kineman and Kumar, 2007) In the relational view, the entire system is causally active.

According to the second law of thermodynamics physical systems must, in the aggregate, progress toward thermodynamic dissolution and disorder. However, it seems poorly understood that this law applies only to energetically closed systems (i.e., when all energy transfers are considered together). In fact we know of no such systems in nature. Owing to isolation by scale, quantum phenomena may come closest to a closed system (prior to measurement); and they exhibit the same kind of relational complexity we would also associate with life. The universe as a whole is obviously not a closed system, having a very large energetic singularity at its projected origin and its projected end. Furthermore, physical systems are defined as semantically (i.e., causally) open systems, which is what the generality of natural law requires. Living systems have the opposite properties. Organisms are defined by Rosen by the unique causal/semantic unity of their internal organization (in terms of metabolism and repair functions). Ecosystems seem situated between the semantic unity of organisms and semantically open physical systems (Kineman, 2003a). Most quantum physicists seem to agree that life involves more than mechanisms. This was certainly evident in Schrödinger's idea that internalization of causes must be responsible for the strange properties of life and the quantum world (Schrödinger, 1943; Rosen, 1999: Chapter 1). It was evident in characterizations of the apparently un-lawful behavior in the quantum and psychological worlds (Wheeler, 1981). Niels Bohr expressed the belief that both mechanistic and finalistic theories are needed to explain life (Bohr, quoted in Margulis and Sagan, 1995: pg. 185).

Hence, just as mechanistic theory projects the ultimate decay of a physical system, relational theory projects ultimate wholeness. Physical systems generally retain differences while increasing entropy (they run down) and living systems form relationships and increase order (they run up). Hence living systems tend toward organization and unity (Ulanowicz' principle of *ascendancy*), a tendency that has also been associated with creativity and purposefulness. Margulis and Sagan (Margulis and Sagan, 1995: pg. 184) conclude that *"life is matter that chooses"* agreeing with Samuel Butler, an original critic of the formulation of evolution as pure mechanism, a view that James Baldwin corrected without much notice (Baldwin, 1896; Kineman and Kineman, 1999). But because life is self-referencing, its ultimate existence in, or progression towards, greater unity of relations seems purposeful; that is, seems to define purpose.

And yet teleological end-directedness has historically raised sharp criticism in the life sciences (Mayr, 1988), these critiques are based on the reasoning that teleology is impossible for a mechanism, with inadequate appreciation for the argument that organisms are not mechanisms (Rosen, 1985b; Mikulecky, 1999). A liberating conclusion of relational theory is that neither thermodynamic decay, nor the taboo against teleology, applies to self-entailed systems while their organization persists. Margulis and Sagan, for example, state flatly that teleology must be a part of science, a view that philosophers have accepted. Relational theory makes incorporation of teleology into natural science possible because of its greater generality.

Rosen captures the idea of finality in the concept of an *"anticipatory system."* Aristotle's "*final cause*," Rosen asserted, "*closes impredicative loops.*" He defined *final cause* as a description or explanation of something "*in terms of what it entails rather than exclusively in terms of what entails it.*" He wrote further: *"And, since we are freed from the exigencies of a single constructive or algebraic time frame, mechanistic objections to anticipation... no longer apply at all.*" He explained anticipation in terms of "*internal predictive models*" that bring the ontology of causation into a system. (Rosen, 1999: pg. 95; Rosen, 1993)

Hence, despite mechanistic objections, the idea of self-directedness in evolution seems inescapable. It has been solidly introduced, for example, in biological evolution in terms of "self-defining phenotypes" and "niche construction" (Odling-Smee, 1988), cultural evolution in terms of creative agency (Banathy, 2000), ecological "ascendancy" (Ulanowicz, 1997), and in regard to the evolution of psyche, e.g., (Wilbur, 1986). In this view, the external direction of life and evolution, which mechanism leads to and many religions proclaim, is at least balanced with internal causation that is much more in keeping with contemplative religions, including the perennial philosophies of the Far East. Again, in relational theory, we find the ability to combine views.

Attributing Ethics to Final Cause

Ethics are obviously end-directed: They are about what we *ought* to do. Hence it is an important result that relational theory can accommodate end-directedness, or anticipation. It is then possible to involve ethical information in relational ecological informatics, including the nature-human interface.

Ultimately society expresses a hope that what we plan and strive for about the natural world is aimed at meeting human needs, improving the quality of life, reducing suffering, and resolving conflict despite diverse ideas about what may be needed to achieve those ends. While conflicts of many kinds, internal and external, seem inevitable, we seem moved to resolve them or rise above them. Such hopes are certainly evident in our literature, art, science, and governance, while impediments and exceptions are recognized as inevitable challenges. Except in our darkest thoughts, these impediments and exceptions are not the goal. They are not elevated to a final *good*, or *human value*, even though they may be considered human nature or a final necessity. If these are fair statements, then we can say that humanity is basically an optimistic species. We might also argue that life itself must be, in a sense, optimistic, as the very nature of adaptation and evolution is to reach new plateaus of existence, whether intentioned or not. To the extent that life can be considered purposeful, as discussed above, the general condition of life might also be seen as a progression towards goals that are system-defined at multiple levels.

It stands to reason then that relational science and informatics should be about discovering and representing the full set of *causally effective goals* along with their relationships to material components of a natural or human system. Rosen, for example, applied relational theory to issues of governance and democracy while in residence at the Hutchins Institute for Democratic Institutions in Santa Barbara. Relational informatics would be suited for representing the effect of goals in a complex system because it is capable of analyzing final causes as *attractors* of system behavior.

Survival itself has become accepted as the de-facto single goal and purpose of life from a passive, mechanistic view of evolution. And yet s*urvival* is probably rarely an immediate goal except in times of threat. It qualifies as a general goal, but that does not necessarily imply proximal importance in the immediate behavior of a system, nor does it require adopting that goal as a source of ethics. Without dwelling unnecessarily on this controversial point, it is important to note that the relational/functional view of life opens the analytic territory to an infinite number of proximal and general goal possibilities. It also validates the idea in general ecology of a diversity of *life strategies*, which, logically, imply goals. Hence we can discuss goals of many kinds. Also, there is no issue as to whether the organism or system in question perceives its goals; that scientists can infer them in other systems can be sufficiently objective. Inference of potentials in living systems can be as empirical as it is in physics, despite their greater diversity. Self-awareness may indeed add complexity, in the sense that an additional closed-loop causality has formed (creating new potentials). But life is already complex with or without self-awareness.

Survival is thus only one driver among an unbounded set of goals that living systems can exhibit and that relational theory can consider. Such drivers are synonymous with anticipatory models. The mechanistic view elevates survival to a supreme goal because it is the most obvious physical result—*presence*. This indeed confers meaning (function in context) because physical presence occurs in context and alters systems. We can therefore discuss the basic *existence function* of life, i.e., the *function* in this case, is existence itself. However we cannot consider it foundational to other functions or goals, or in any sense more important to an analysis. For example, in Rosen's view a tree objectively possesses an internal model for future seasonal conditions and that model drives its anticipatory behavior. The model for seasonal anticipation can be studied empirically and its function can be determined and recorded for informatics. The existence of the model is objective and its study is empirical. While studying the function of this model, we may also interpret its meaning in terms of goals. It is common, then, to say these adaptations are *for* survival and equally *from* survival. However, the more proximal goal that exists as an actual potential of the system, is the seasonal change encoded in the model, and that is the useful unit of analysis. It may as well lead to extinction as survival (Rosen and Kineman, 2004). Natural selection, therefore, does not produce or explain the existence of goals, it selects them.

We may consider that the urge to reproduce anticipates death and represents just such a model, and in that sense we may discuss the very general goal of *survival*. We know from human experience, however, that the most general goal may not be, and perhaps rarely is, the proximal goal driving behavior in the present. As a goal, *survival* can be a gross over-simplification of the purpose(s) that drive life. An analogy might be to say that returning to one's chair is the goal of dancing, whereas those who dance say the goal *is* (sometimes) the dance. In fact, it is a strange reversal of the mechanist paradigm to accept any goals at all; an admission that semantics must be considered. The fact that survival could not be dispensed with along with all other semantics expunged by mechanism, does not mean that it is the only or supreme goal. It means that even mechanism, the strongest antidote available, cannot eliminate purpose.

The inability of the mechanistic program to completely eliminate the implication of final cause is an important result. We should then admit that whatever general system in which we believe will necessarily imply an ultimate purpose. When we open the question in this way, it is clear that more than one general system can be identified. There is an implicit world of the mind and spirit that is as much general as the world of material existence. Both, therefore, can have causal effects attributed to the whole, and both may be limited or 'hidden' by proximal relations. The mechanist, therefore, has the same ground for claiming material existence as a final goal as the spiritualist has for the same claim about spiritual existence, or the goal of Divinity. Both are potentially legitimate claims from a relational perspective, but neither is elevated or diminished, as the two sides represent the fundamental *mind-body dualism* that cannot be decided in favor of one or the other. Their active, causal presence in a system is, in both cases, axiomatic as logical end-points of the broadest possible context in each domain. They undoubtedly feed into more proximal drivers, both psychological and material. The relative mix of ultimate and proximal motives is open to empirical confirmation and modeling from a relational point of view. A very broad array of motivations may exist that factor together in a complex system to drive behavior. Not all of these are realized, and hence we should consider them existing as potentials of a system.

Ethics may then be associated anywhere on the spectrum from proximal to general goals or values. We must, however, set aside the idea that mechanism is supreme either as explanation for nature or as a source of ethics. The relational mathematics is clear on this point; mechanism is one subset of a more general existence governed by *mind-body* (treated here as *information*) relations. The relative status of *living* vs. *complex*, however, remains a thorny philosophical issue; as it is one thing to say that a complex world precedes a mechanistically simple one, but for many it is not acceptable to call the relational world a living one (aside from organisms), thus opening it fully to intention. Still, the living world shares far more with the complex world than does the world of mechanism, which is essentially its antithesis. If we adopt the more general proposition that relational complexity is the primary ground of existence, it becomes the ground from which life rises to explore creative potential while mechanism describes the result when potentials become actualized. The present, where deciding takes place, appears as a complex of functional influences that are yet to be resolved. This sense of the *unformed present,* filled with attractive potentials, or goals, is the ethical domain presented by relational theory.

Environmental Conflict and Opportunity

If relational informatics can facilitate greater understanding of nature and society as a relational system, as claimed, it should be able to aid resolution of environmentally-based conflict simply because a greater understanding of the dynamics of relationship can be a bridge over seeing a system as comprised of discrete entities and consequently our choices in management as being equally discrete. Relational systems hold far more opportunities than any mechanistic analysis of them can reveal. The essence of conflict resolution is to recognize the value in diverse views, to find common denominators, and eventually to transcend difference on an entirely new basis (Hunt, 1995). This is a description of the emergence of opportunity from conflict, a process that can now be seen with more clarity from a relational theory perspective.

It is first necessary to consider the influence that science has on our social and political world. In a rich field of literature on this subject, the philosopher of science Thomas Kuhn has perhaps most clearly made us aware that science itself is a social phenomena, subject to its influences and returning equal influence. It is not surprising, then, to claim that the basic duality of mechanistic thinking in science has spread throughout society, inspiring many replicas of its world view. As values cannot be conceived of except in terms of the subject-object dualism that pervades modern science, humans must then be considered the source of values and sole instrument for their construction. This basic duality has been identified with a psychology of fear and control, leading ultimately a culture of inner and outer conflict

(Jung, 1957; Watts, 1960). A cultural preoccupation with the mechanistic perspective may thus inform and reinforce a limited and potentially destructive social philosophy.

Conflict has many justifications from a mechanistic perspective: “sociobiology,” “selfish gene,” “survival of the fittest,” “manifest destiny,” “laissez-faire,” “holy war,” etc. The program is a simple one of identifying opposites that can be characterized as conflicting. Relational, and deeply ethical points of view lose ground to such mechanistic simplicity where there can be no middle ground between opposites, no true emergent phenomena. From duality, utilitarian views of the value of nature to Man tend to prevail, because if we are separate from and in conflict with nature, it is only our dominance and control that will benefit us. This point of view must then frame value as instrumental in content, and human in origin. While the source of value that one presumes does not dictate its content, and in that sense even human constructed values can be real and natural, they nevertheless are similarly restricted by the human vehicle; for when we view both source and content as being owned by humanity alone, we may cease to imagine that there is something to respect outside ourselves. Bateson described it thus:

> *"If we continue to operate in terms of a Cartesian dualism of mind versus matter, we shall probably also come to see the world in terms of God versus man; élite versus people; chosen race versus others; nation versus nation and man versus environment. It is doubtful whether a species having both an advanced technology and this strange way of looking at the world can endure…If you put God outside and set him vis-à-vis his creation and if you have the idea that you are created in his image, you will logically and naturally see yourself as outside and against the things around you. And as you arrogate all mind to yourself, you will see the world around you as mindless and therefore not entitled to moral or ethical consideration."* (Bateson, 1972)

Relational co-existence is a more difficult concept than mechanistic separation. But a means for integrating values and seeing stronger relationships between human and natural values could help reduce the motivations for conflict, or help in resolving them. While conflict and peace may both be 'natural,' the ideal of peace seems to exist when we generally wish *knowledge* (science, experience, and wisdom), *action* (policy, governance, and development), and *belief* (ethics, philosophy, and religion) to work constructively together.[35] Peace is not merely the absence of conflict. That goal, I believe, is what produces social progress, whereas conflict is an attempt to sort out the past, and to arrive psychically at the point of recognizing true options, most of which were already present.

If nature is a storehouse of knowledge, not just about the material world but also about the functional world that can inform values, then constraining rational thought and empirical study to the practical issues of state and society, or restricting the consideration of value to strictly anthropocentric values, indicative as they may be of aspects of nature, would be an obvious limitation. To imagine beyond our own boundaries is both the gift and challenge of humanity. And yet without a holistic perspective—an "*extra-mundane point of reference*" (Jung, 1957)—where the values associated with the perception of immediate differences can be combined with values associated with the perception of immanent and contextual relationship, society fragments into conflicting ideologies; we do not "see the forest for the trees." The situation is described by Jung's concept of the *"split mind"* at both individual and societal levels (Jung, 1921). Dissociation between these two value perspectives,

[35] I refer to these three concepts elsewhere as corresponding to three primary paths to enlightenment in Vedic philosophy: *jnana* (knowledge), *kharma* (experience), and *bhakti* (faith). They are commonly thought of as the three primary pathways to God (or Truth): pursuing wisdom, experiencing the consequences of action, and being devoted to a universal principle of love. In Vedic teaching, all three are required for a balanced mind that is in tune with the present, although it is *bhakti* (love) that must lead in order for the result to be constructive. Similar concepts are expressed in Christianity and other religions.

which I will simply call *"partial*" and *"whole"* (between which sits the relational), leads to the mind's attempt to re-integrate, through images of wholeness (Jung, 1959), or to defend traditions as a means of protection from the 'threat' of wholeness. Misunderstood, wholeness seems to destroy the status-quo of separate systems, whereas in reality the relational whole can incorporate them, support them and guide them to greater prosperity.

We humans seem to live in a whole-part dichotomy at personal to societal levels, and certainly within the current scientific views. A great deal of anguish has been experienced with regard to which of these views is 'best.' At least with regard to science and informatics I have attempted to show that each has equal value for different purposes, but that it is their combination that can lead us to new solutions for the kinds of complex problems we are increasingly facing. The extension of this philosophy to societal and ethical levels is not far-fetched, as I have tried to show. The relational world view is capable of integrating diverse scientific and cultural models at a foundational level.

A change in basic orientation about the nature of reality (or the 'reality' of nature) that is called for today and that relational theory charts, should have an important impact on both science and society. We know from history that ideological shifts have been responsible for major social and political change. Valuing the co-existence of differences is a first step. It should be a familiar one, because it is the basis of the adversarial legal and political systems in most democratic countries—systems that have proven their worth through the test of time. These systems owe much of their success to the simple recognition and subsequent respect for differences, including the recognition that while differences may conflict on one level, they can be supervened by sound principle. This level of awareness alone, requiring reference to transcendent principles and doctrines, removes the first cause for oppression of people and ideas—the belief that differences should not in some sense have equal status.

Our legal and political systems are often seen as ending with a decision as to which side is right or should prevail, but this is not the whole story because each case also encodes legal principle in which advancement of law itself more often depends on finding the truth in both sides. This is why law should never become a set of axioms, but must always remain a human exercise, seeking the spirit of the law to inform the letter of the law. In just this way, the recognition of equality among opposites requires a transcendent awareness that one may lose sight of if it is thought that only opposing positions have reality, and ethics are a matter only of deciding between them. In that event, regarding both law and policy, society begins to descend into a cultural dilemma of under-informed and over-defined choice. The polarities then consume us as choice becomes meaningless and in any case, balanced with equal adherents. Societal forces today have become so adept at forming perfect opposites that we increasingly have situations where no clear decision can be made between them. This, perhaps, is the point of failure of the doctrine of social constructivism if it does not involve other contextual levels where values may also be referenced; it is only constructive until it reaches the perfect impasse that cannot be transcended.

As in the similar limits of "finitary" mathematics, there must always be an external semantic reference, a larger system, in social systems to resolve such paradoxes that naturally arise from any mental model. In the ‘perfect polarity’ we confront the mathematical problem of deciding which the majority view is where each view has an indistinguishable number of participants. This is the point where any system of choosing between opposites fails, and solutions focused solely on swaying the balance have no power against the perfection of these opposites (well into the realm of uncertainty) as a result of increasing cultural sophistication. In other words, when a whole is fragmented, it is theoretically possible to identify a perfect duality, and with experience and in response to social forces, we will eventually do so. In that case, where I believe we are today, socially, politically, scientifically and ethically, we must revise the second step of the adversarial process—that of selecting between the options.

We need what I will refer to as a “*third alternative.”* Just as systems always produce a third “emergent” system when combined or when they interact, this third alternative is implicit in every conflict—it is some combination of the two opposite positions, or an entirely new awareness that renders the difference unimportant. I present this rather obvious fact as an alternative for two reasons; first, because it is often overlooked when two (or more) sides are firmly entrenched, and second because it is not always the best option if indeed the positions taken do not map out a true “coincidence of opposites,” a true duality (in which case even their combination remains partial and subject to further conflict). For this third alternative to work, one must do a great deal of work to identify the inherent duality that underlies the conflict. It is for this reason, not a trivial recommendation. The Civil Rights movement of the 60’s pitted individual human rights against cultural identity: the hope of gaining and the fear of losing a better life. Which identity was the more important? In what resulted, it might be argued that both had to change into new, more compatible distinctions that could co-exist and approach more common challenges. It required a higher calling of both groups.

Conflicting ideas may first result in various forms of battle, be that discourse, legal process, political process, or violence. The very premise of battle is inequality, generally of both perceived value (of the other position) and perceived strength (the use or further insult of power). It is because of that perceived inequality that each side believes it should prevail, and that it can prevail (even by revealing an abuse of power as in Mohandas K. Gandhi's strategy of *satyagraha*—non-violent resistance). Indeed, when put to the test of battle, one side may prevail in the material world and the other side may prevail in the moral world. Without complete resolution, the battle will be fought again on another ground; for when equalities of one sort are ignored, differences of another sort try to redress the injustice, and the process continues. Conversely, if there is conflict, it is certain that some equality has been ignored.

If the process of conflict is not transcended, it will naturally drive toward the incontrovertible nature of duality—pure opposites, neither of which can be eliminated. Such unenlightened conflict can thus end only when both sides achieve full equality, leaving some form of transcendent unity as the only remaining option that will allow the system to continue existing. This was indeed the case regarding cessation of the Cold War, two factors being (1) scientific evidence of a 'Nuclear Winter' scenario, meaning that a hemispheric nuclear conflict could not be won, and (2) realization that a continued standoff, requiring equality of armaments, was not affordable. In other words, our choices as a global society were to destroy ourselves, go broke, or find another way. On that one occasion we chose to find another way; a choice that may have been more natural than to any great credit of wisdom.

The emergence of transcendent awareness may be natural precisely in the above way, where some basic instinct for collective survival rises above the instinct for individual survival (Jung, 1957). If the implications of relational theory are correct, a larger system in which perfect opposites can be related and in some sense unified, is always present; it must be, because in the relational theory the unified whole is also the explanation of where the opposites were drawn from. It appears that the main courses of action open to individuals or societies are two: seeking such transcendence, as early as rational and ethical minds can integrate the disparate positions, or waiting to be driven to it by social and political process. For all living systems adapt to context, and living systems held in a context of conflict will thus adapt to perfect the duality inherent in that.

However, I do not mean to state any necessity for the "perfect opposite" to form before society can remove conflict. It is a theoretical point that a system in conflict will be driven toward, but at any point a transcendent view could be identified that dissolves many differences. If, on the other hand, society limits itself to a system of conflict where choosing between alternatives is the only method, I believe it will eventually reach the perfect irresolvable conflict—a true crisis. The rational mind is capable of transcending to new levels of understanding at any point in this process. In other words, we can juxtapose the entire polarized or polarizing system with something new. And yet this itself is not a moral judgment, because a great deal of social, political, scientific, and ethical refinement may be required to reach that point, to understand the paradox society must eventually face.

We may, in fact, be seeing the beginning of a transcendent discourse of just this type. Two devoted environmentalists (Nordhaus and Shellenberger, 2007) have sharply criticized the environmental movement in the US, as have others Cronin Guha, for taking a narrow preservationist view that, aside from being impractical in modern society, may be counter-productive in terms of preventing more creative options from emerging from the combined values of ecosystem sustainability and human progress. Unlike other recent authors who have filled the semantic vacuum in common information (discussed above) with unnatural philosophies about nature—including Bjorn Lomborg's (Lomborg, 2001) deification of economic and technological value, and Michael Crichton's literary capitalization of public uncertainty about global warming (Sandalow, 2005), Nordhaus and Schlesinger attempt to point to the third option that is in some way integral with the naturalist perspective. Whether any of these attempts hit their target is not the point here, but rather that we are witnessing a social phenomenon where a void in semantic knowledge has created an opportunity for fame and fortune while the problem grows worse, and while the third option is dawning it now begs for better information about the deeper functional entailments of living nature, from which new opportunity may be found. Other 'positive' approaches perhaps more aligned with the green movement, can be seen in the rising fields of "Bioneering" (Collet and Wyatt, 2005) and "Ecoprenureship" (Anderson and Leal, 1997) where a new suite of technologies based on biological and ecological "design" are being explored.

The role of relational theory in conflict resolution can therefore be stated this way: By providing a framework where two reality concepts—partiality and relatedness—can themselves be integrated as equally valid aspects of every situation, relational theory then provides a pathway to conflict resolution; for conflict is a choice to place greater importance on difference than relationship, and it can be a reasonable choice only when both realities are recognized. Transcendent awareness might thus be viewed as a mapping into greater contextual levels of causality and possibility. This does not then carry the immediate judgment that either conflict or unity is the better choice, but that together they constitute a richer and more value laden system from which choices can be derived. As a greater overall good, peace seems to emerge as a dynamic attractor. It seems obvious that peace can and does co-exist for most people and societies, even as the ultimate purpose of conflict.

We should remember, however, that conflict can arise from forced unity (as in the resettlement of Israel into Arab lands) as often, or more so, than when differences are allowed to take their course. Thus while unity may not be the immediate answer, recognition of its presence and potential even in situations of extreme opposition, may still preserve the highest nobility of Mankind. Even war is not possible without unity of many kinds and at many levels, and which war has been without great moments where enemies see each other's humanity, sharply contrasted with the pain of duty? These issues have no resolution of themselves, they are the true moral dilemmas that great epics are written about. They are resolved only by transcendence, and that requires first the recognition of an ever-present relational unity.

Deep Ethics

I have described how relational theory presents communication and relation as the fundamental aspect of nature. It describes a *suchness* not unlike the *ground of being* discussed in Vedic, Buddhist and other contemplative practices (and re-emergent in Christian contemplative practice). Just as any theory projects its basic premise onto the presumed reality and whole of existence (recall the projections of mechanism), this one projects the reality of a relational whole or unity. Hence, what we might otherwise view as a psychological construction, either by the organism itself or by an observer, we may in the relational view see as a principle drawn from nature—from the nature of living entailments. This provides a ground for considering ethical content in or from nature—a principle of unity underlying the differences we see and experience, and toward which life is drawn, both by evolution and consciousness.

Ethics can be derived from *instrumental* values or from presumed *intrinsic values*: two views that have existed in opposition but can be integrated by the relational theory (Kineman, 2005). I argue that the recommended change in natural philosophy, information theory, and corresponding practical fields such as ecological informatics, should involve both value bases. Accordingly relational informatics can be both pragmatically and naturally ethical in that it can consider the effect of assigned values as human functions in relation to other components of the system being considered, while also inferring natural values as principles, expressed in the form of, or implied by, empirical ecological functions. The later has been difficult to argue (i.e., transfer to human value) from the perspective of revealed truth. Outside of a natural context where the functional source and effect of such principles can be subjected to experimental confirmation, the idea may be wrongly interpreted or miss-applied to create a further sense of alienation rather than kinship with nature (Cronin, 1996). The ability to fantasize about nature is so obvious that it undermines good intentions and sets up an easy rebuttal in the form of equally fantastic counter-values. Guha, for example argued that the American movement that formed around Deep Ecology is destructive because it is a product of the wealthy who have time for such ideas, and it exports a preservationist ethic on people who can't afford it; those who are more involved in the earlier stages of Maslow's "hierarchy of needs" (Guha, 2001). While such conflict is real, it does not mean that either value is wrong; but that their applications and effects should be understood and balanced in some just way.

Instrumental (or applied) values are those of human origin that are projected onto or assigned to nature. *Intrinsic values* are presumed built-in values, given by nature itself. Instrumental values, being human inventions, are open to various forms of measurement, arbitration and accounting, and are thus easily associated with science, politics, and economics. Intrinsic values, being given (by nature), are open to discovery through outer or inner directed experience.

It is important to clarify this difference: The outer-directed view looks for regularities in measurements (including measured values) and adopts them as general truths. The inner-directed view looks for regularities in experience (including experienced values) and adopts them as general truths. This basic duality is central to the discussion of ethics in human relations. While it is clear that we can assign instrumental values according to our preferences, it may be less appreciated that we also have the ability to uncover intrinsic values by looking deeply and reliably into the core of our own relational nature and, by analogy, similar relations in the rest of nature. This latter point, as will be discussed later, is the essence of many "wisdom cultures" such as Zen or Mahayana Buddhist meditation and ancient Vedic philosophy from which these practices came.

It should be clear from earlier arguments that ethical content cannot be conveyed by facts alone, divorced from their original semantic contexts. However, meanings can be recorded in terms of multi-contextual functions, introducing them from a study of nature and humanity. The principles of "Deep Ecology," (Sessions, 1995; Dival and Sessions, 1985), despite the criticisms of how its values have been interpreted and applied (e.g., Guha's criticism[36]), represented certain intrinsic values derived from nature, or at least from contemplation of nature and thus inner human nature. The core values of Deep Ecology constitute cultural wisdom derived from many centuries of introspective practice. The deep ecology movement called for a major *"ideological change"* to more naturalistic and even spiritualistic ethics. Its principles and ideology go back to the "perennial philosophy" and the oldest known ethical works of the East, the Vedas and Upanishads of India, the teachings of Mahatma Gandhi (Gandhi, 1958), and Mahayana Buddhism (Zimmerman, 1993). Taping into this tradition, Dwivedi argued that a culture has emerged, in industrialized society, that is basically violent towards nature as a result of its religious and scientific beliefs (Dwivedi, 1990). The philosopher, Allan Watts,

[36] The American Deep Ecology movement has been criticized for formalizing these values into a radical protection ethic. But just as modern Hinduism or fundamental Christianity reflect only a popular image of their original, deep spiritual roots, any applied ethical system can transform from one of pure inspiration to one of institutionalized dogma and aggression. "Environmental terrorism" differs little from the Medieval Crusades in this regard.

suggests that a basic mistrust of nature developed along with the belief in our separation from nature, leading to an increasingly fearful need to watch and control it (Watts, 1960). In contrast, ancient Vedic philosophy (which deserves classification as philosophy rather than religion, no less than Greek philosophy does) held that all creation is equally divine, and that man, being its highest creation, therefore has the greatest duty (dharma) to care for nature and all creatures.

The boundaries between instrumental and intrinsic value perspectives are not neatly drawn between cultures and religions. The labels *Eastern* and *Western* refer primarily to cultural origins, whereas the division today is archetypical–a frame of mind—and mixed throughout societies worldwide to varying degrees. Nevertheless, the duality persists as alternate views in human consciousness that may indeed fit Jung's image of the "split mind," exhibiting dramatic opposites as a means to re-discover the whole. That whole must be some combination of intrinsic and instrumental values (Kineman, 2005).

Environmental ethics in Western philosophy are most commonly justified on the basis of instrumental values alone, such as:

(1) Humans are "helped or hurt" and otherwise intimately involved with the natural environment.

(2) Ethics apply to all human affairs.

(3) Therefore ethics should concern the environment, for reasons of self-interest (at least). (Rolston III, 1988)

Holmes Rolston III criticizes this view of nature as only "secondary," solely an object of human use and moral projection. He argues for intrinsic value, on which one can build a further case for *"respect and duty"* ("dharma" in the Vedic traditions) to nature, contrasting this with the *"anthropocentric, personalistic ethics now prevailing in the Western world,"* in which nature is considered *"amoral"* because it *"has no intrinsic value."* Rolston argues for objects of value in nature to which ethics can apply, and he attempts to extend this to imply that value itself may be considered natural. He lists multiple ways in which such value can be applied:

(1) Nature can *"carry"* human values in ways that can be objective (e.g., nutritional needs) or subjective (e.g., symbolic assignments);

(2) These carried values must in some sense have real elements that we can discuss as *"experienced"* or *"unexperienced;"*

(3) The act of valuing, like science, may itself be a valid way of "knowing" about the natural world, implying a domain of all possible values knowable from nature;

(4) *"Following nature"* is neither trivial (i.e., automatic) nor unnecessary (it provides ethical meaning). Hence it cannot be true that everything *"follows the laws of nature"* if human capacity exceeds law-like behavior in this way. Morality must then be seen as either intrinsic, or a necessary addition to nature.

(5) If morality exists in a domain of *"human deliberation,"* options for *"following nature"* include surrender, conscious mimicry, or spontaneous and creative involvement, as with Man at the helm of a ship.

(6) Nature can provide ethical feedback in the form of tutorials as a mysterious story of life including human life that we would be wise to read. Nature as

analogy can thus inform human moral principles, even if it is not considered strictly the source of them.

(7) Moral relations with nature begin with recognizing *"good"* in the fact that nature contains objects of value that humans can and should appreciate or even love. This generates a sense of *"respect and duty"* to nature.

Rolston wrote: *"In an ecological perspective, that Earth is valuable would mean that Earth is able to produce value and has long been doing so as an evolutionary ecosystem."* But the instrumental view cannot go so far as to say that nature produces ethics, even though it produced ethical Man. Man achieves special powers that allow moral conviction and the assignment of value not by surrender to natural forces but by separating from them to join God in the same domain where mechanistic science places natural law. Ultimately, from any instrumental argument, nature itself must be "amoral." Rolston tried to rescue the situation by writing *"sentient animals, plants, and ecosystems may be of value that counts morally even though they are not themselves moral agents."* Limited by objective perception he is then led to say that *"nature is not sufficient to produce these virtues."* Even Rolston's qualification that *"it* [nature] *is necessary for them* [virtues]*"* leaves ethics a human invention from this perspective.

Prime describes *"Vedic Ecology"* (Prime, 2002) which assumes a priori that nature is sacred or holy, and as much endowed in every part, including humans and all creation, with the qualities of Divinity. This shares the wholeness of the relationally complex view that nature, being unlike a machine, does not require an external origin or creator, but that origins can be internal and consequently shared with the whole. The need for environmental ethics can then be justified more directly from this view, that:

(1) All of creation is sacred (or divine),

(2) Humans are the most endowed members of creation; and

(3) Humans therefore inherit the greatest responsibility for stewardship of nature, which is then expressed ethically.

The Vedas and Upanishads (Vedantic derivatives) of India speak of a single interconnected reality, which we see through the veil of *Maya*, which is illusion and the world of measurement;[37] but which emerges from a creative principle that exists in all parts of the universe and the whole. The 5th Chapter of the Brihad Aranyaka Upanishad, called the *"Madhu Vidya,"* or *"honey doctrine,"* refers to one animating principle that is universal and reflected in every natural system of the universe. The same principle in each part is in the whole and vice versa. This was translated by the theological scholar, Max Muller, as a *"bright, immortal person"* (Muller, 1884), and more recently as an *"Immortal Luminous Being"* (Krishnananda, 2006). In Muller's translation, the Madhu Vidya states: *"He indeed is the same as that Self* [Atman] *that Immortal, that Brahman* [universal source]*, that All."*[38] In verse 15 it states: *"And verily this Self is the lord of all beings, the king of all beings. And as all spokes are contained in the axle and in the felly of a wheel, all beings, and all those selfs* [existences, referred to above] *are contained in that Self.* (Muller, 1884)

We thus see in these writings a philosophy where the whole is immanent in the part and the part is constituted in the whole. Humans inherit specific duties and

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[37] "Illusion" should be taken as *a false image of reality*. This does not invalidate its effect, only its apparent source—things are not as they seem.
[38] Authors' explanations in brackets [ ].

owe respect to nature, without which humanity itself is diminished. We are not free to change these responsibilities, but rather it is life's challenge that we remember and live in accord with them (the concept of *dharma*, or proper action), or incur the natural consequences (the concept of *karma*). As nature's highest moral product, mankind has a stewardship duty to nature not unlike the duty one has to parents. Valuing nature in this intrinsic way is synonymous with valuing one's extended *self*. Moral questions, in these teachings, are more often a matter of reconciling *dharma* and the equal power of pure love (*prema*), than they are about the drama between concepts of *good* and *evil*.

Figure V-5 shows *"Five Human Values"* that are considered to be fundamental to the reality of conscious life in Vedantic philosophy.[39] These are considered eternal values that are both natural and at the core of humanity. Vedic teachings are being revived in India, for example by Sri Sathya Sai Baba, and their principles are being translated into secular education in a program called *"Education in Human Values"* (EHV) (Burroughs, 1981). EHV is being introduced to schools and universities internationally by the International Sai Organization. In this concept there is a component of teaching in every course, in all

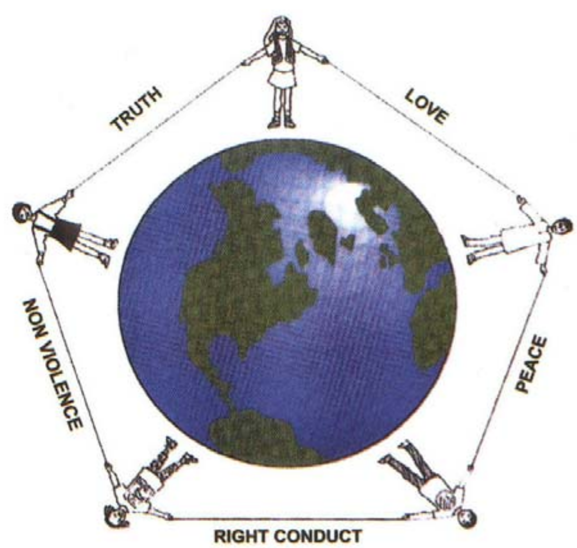

Figure V-5: Vedic "*Five Human Values*"

[39] From the teachings of Sri Sathya Sai Baba, Prashanthi Nilayam, India

subjects, on how to use the acquired knowledge ethically. Many examples demonstrate that it is not difficult to incorporate similar ethical values into Western environmental education (Engel and Sturgis, 2006; Appiah, 2006); but rather it is a matter of choosing to do so.

Prime, like Dwivedi, argued that different ethical orientations result from the radically different approaches to man's place in nature exemplified by Eastern and Western philosophy. The instrumental view of man separate from nature is, to Prime, the root of materialistic and reductionistic approaches to nature, and that orientation limits an ethical framework to human invention. Even its approach to knowledge requires Man's separation from nature. The content of that knowledge necessarily confirms Man's separation and nature's lack of values. From the separate perspective, value must be an extraneous input, either from Man or from a separate God. However, in the Vedic perspective Man is both natural and divine, and by discovering Man's 'true' nature, or true Self (called the *Atman*,) we will also be discovering true principles of nature. In this view, the true self can also be known from nature, but only through the filter of material deceptions, which one must learn to see past as an advancement of human consciousness. Prime wrote:

> *"In the Vedic vision of the world, consciousness pervades the universe and all within it" This is the core of "sanatan dharma" which Prime translates as "the eternal essence of life." He wrote: "This essence is not limited only to humans. It is the essential quality that unites all beings – humans, animal or plant – with the universe that surrounds them and ultimately with the original source of their existence."* (Prime, 2002)

This view leads automatically to ethical responsibility, as a part of our natural Divinity, and application to surrounding nature because it is equally divine. This results, for example, in three ethical principles for Vedic ecology: (1) we are all one family (*“sarve bhavantu sukhinah” – “Let all beings be happy”*); (2) no one should take more than is needed (Isa Upanishad: *“Take only what you need that is set aside for you. Do not take anything else, for you know to whom it belongs.”*); (3) we each have a responsibility as a teacher and a leader of divine principles (such as nonviolence, tolerance, inclusiveness, etc.). These principles become expressed as ideas of harmony and balance with nature, synonymous, as Wilbur puts it, with being at peace with one’s transcendental self (Wilbur, 1995).

Just as the spiritual imagery points to something beyond it—a sharred essence—the scientific imagery, or description, must also point to something beyond it. In the case of relational theory it appears that it can be the same shared essence. In the limit of relational theory (its unbounded extension), the holarchy of contexts contains the source of all existence and a pervasive principle of abstraction and actualization. It implicates a creative reality at the root of all systems and especially magnified in life.

Filling the Semantic Vacuum

I have argued that incompleteness of information as evidenced by non-communication of natural functions is the likely cause for the current failure of ecological information to communicate effectively between science, policy, and ethics (Chapter One). This situation results in semantic vacuum in which arbitrary interpretations of facts removed from their original contextual meanings can be supplanted. It is then possible for policy analysts to characterize environmental science today as little more than a hired gun for politics (Sarewitz, 1996). As a result some analysts and politicians argue that we are wasting money on basic research; that if science is the slave of policy we should let policy decide its priorities. I argue that we can avoid such a failure by repairing our concept of information such that it communicates properly. When we dissociate facts from their natural context, and when we do not have a universal set of natural laws for interpreting that class of facts (the complex), it is then possible to invoke human interpretive myths, driven by various motives, in their place. This creates a climate of unreasonability around ecological discussions in which unrealistic positions can define the poles of social debate. Correction requires information, that is, contextual semantics, but our very concept of information has ensured that natural semantics will be excluded.

Knowledge of truth, or natural ethics, can come from human sources, as is evident in art, because we are natural. Humans came out of nature, not into it as complete aliens. I would argue, as many have, that human nature strongly reflects living nature in general and is to some degree indicative of it, except for levels of abstraction that may diverge along various lines of imagination. Through imagination, we create new realities that may become natural. Hence the socially relative system of adding value to data, which I have criticized for not retaining enough natural knowledge through the preservation of original semantics, is not therefore lost entirely. In fact, a deep understanding of human nature through deep introspection would arguably be sufficient to recover natural wisdom. But in a society ruled by mechanistic models of reality, introspection is discounted as a source of information; and such practices, although they have often inspired the greatest scientific insights, are not openly admitted into the scientific framework.

It seems reasonable to assume that there are limits to the power of imagination too. Not every superficial abstraction we might generate is realizable in nature – it can be truly divergent and destructive. To inform our experiments in human imagination—experiments that would otherwise gamble our health and survival—we have the content and communication of information; which is now called *informatics*. The role of experts may need to retreat to improving the content, for their final interpretations less and less being accepted as authoritative compared with skilled writers and political or economic advocates. We should therefore attempt to build an informatics that, while not self-interpreting, nevertheless communicates meaningful content at every level, retaining original contexts. I believe that task involves building informatics on the concept of structure-function relations within relational complexity theory.

In assessing the impact of such relational informatics on science and society, it should first be understood that our past information approach has resulted in extremely uninformed social conflict, for which there is no natural or socially constructive resolution, quite literally because it has no source of meaning (other than possible future meanings). Most of this conflict is over structure not function, syntax not semantics, form not substance. In this sense, if the situation is not corrected, the critics of science will be correct; science will become a social and political pawn. The situation is not quite that dire, however, because it is possible, as I have mentioned, to add back some of the lost meanings through human expertise and wisdom; from those who can reach deeply introspective or highly transcendent levels and those who know natural systems well through intimate and long-term experience. Such people exist throughout society, and in primitive or native cultures, but they do not dominate unless they also have political skills. We thus have some stories of marginal success, where introspective knowledge has had an impact. But as the present situation continues, even these experts are being held in suspicion or discredited for lack of a evaluative context in which their methods and experience can be seen as more reasonable than less informed ideas. We therefore need an avenue for natural knowledge to enter scientific information itself, and I believe relational informatics can provide that.

With more appropriate informatics, in which ecological reasonability can be better known, just as physical reasonability is widely known, life science may obtain more solid ground in guiding creative human development and establishing the boundaries for policy or management debate and action. The effect on science should be to better unify "hard" and "soft" sciences and thus broadening our world view. The effect on management, policy, and decision making should be to improve understanding and communication of natural alternatives for action and to reduce the impact of literary or oratorical presentations that merely appeal to preconceptions without actually informing. The effect on society should be to move discussion of pressing issues toward more realistic alternatives, realization of transcendent possibilities, and away from the sharp polarities that generally lead to increased conflict. Ultimately, as Bateson argued, the foundation of cultural thinking will need to shift toward relational ideas and away from strictly mechanistic modes of thought; where a transcendent awareness can develop that incorporates mechanistic thinking but is not limited to it.

The proposed change should not, however, dictate a new ethic, such as conservation vs. development, holism vs. individualism, cooperation vs. competition, or intrinsic vs. instrumental values, except as these may emerge from the entailment of our knowledge about relations in nature. Recognizing that the semantics of holistic system levels (wholes) can indeed have an effect on the origin, fabrication, and behavior of sub-systems (parts) does undeniably introduce a governing system principle at the highest (or unbounded) contextual level, which some may interpret as God. As argued above it is also consistent with the idea that this ultimate, unknowable reality is reflected within all sub-systems more or less holonomically. This, of course, can be aligned with spiritual concepts of the inner Self. It does say that everything is connected to everything else, as the ecologist has always sensed. However, every reality concept carries an ultimate implication, an implicit god, as its logical extension. As I have shown, mechanism does this very clearly by externalizing natural law, and it has accordingly made peace with the Church. But it is more important today to adopt a view that allows integral thinking. The question should be if our world view allows consideration of deep, or even ultimate semantics, without obscuring the effects of proximal relationships that we can study empirically. The new informatics should exist as a foundation for understanding and integrating multiple belief systems or proposed actions, and for evaluating alternative possible futures that support both the creative diversity and systemic roots of human and natural values.

In 1975, Joseph Needleman declared that the *"dream of manipulating nature to reinforce our egoistic purposes,"* was dead for obvious ecological reasons (Dival and Sessions, 1985: pg. 82). Much earlier, Nietzsche declared that *"God is dead."* Both announcements have proved quite premature; these two forces in our consciousness will likely do battle for some time to come. As we saw above, the new relational view of nature, which is nothing less than revolutionary, does not reject the mechanistic or instrumentalist orientation, and accordingly it cannot reject the perception of separate values and benefits. Nevertheless, a change is needed. Even if we accept the goal of manipulation, our relationship with living nature seems to be one of far more dependence than many would like; and it is not yet interdependence. There are feedbacks in ecology and a long-term survival strategy will require us to establish far greater mutual benefits. We will need to return as many support functions, goods, and services as we take. In fact, the accounting of our ecological relationships that was recently done (Millennium Ecosystem Assessment Board, 2005), cannot characterize our current role in nature as more mutualist than parasite.

Just as we must step outside the world of numbers to find natural referents and thus meaningful (semantic) content (Chapter Two), we must here step outside the world of symbols to find human purpose. I will use a modernist interpretation of James Joyce's Ulysses to illustrate the point, suggesting a perhaps not too unlikely analogy between Ulysses and our stories of nature. Secari wrote:

> *"I am acutely aware that this thesis will meet with some resistance because it is still somewhat unfashionable to assert that any work of literature, no less a work as complex and heteroclite as Ulysses, can be approached as having established a fixed center, a transcendental significance that governs its meaning. Inherent in my argument, then, is the contention that Joyce's allegory is a hallmark of modernism in its attempt to defy reductionist accounts of ideals as the result of mere human construction and to point to an event outside the web of language that can ground our idealism. Outside of language is the Christ event; outside of words is the Word."* (Secari, 2002)

Similarly, we can see in the relational theory applied now as a model for social construction, that it fully integrates the ideas of constructivism and realism by being both prescriptive and descriptive. It does this by proposing natural, intrinsic models in nature, but then allowing them to construct natural systems, and vice versa. The implicit holarchy points always to a semantic outside that is available through a semantic inside, a larger system that can never be reached but is nevertheless real and a semantic inside that has the same characteristics as the universal. Furthermore, we can see in the relational theory that such meanings themselves can influence material development. The theory thus meets fairly with many contemplative spiritual views, in the traditional sense of a transcendent source (*Brahman*, the "Word") reflected in a much more employable source within (*Atman*, the "Christ"), as suggested in Secari's transcendent view of meaning in Ulysses.

Social values may indeed require community and discourse to determine or even to discover, but by this model they are not established only in that way, and are not void of natural sources of truth, which we share. There is always the possibility of inheriting value from any whole aspect of nature. In this way, I believe, we achieve what Rolston was aiming at—a reassertion of natural value as emergent from constructed values, and also what Prime and Naess were aiming at—a central acknowledgement of a deeper source of truth. As in Sacari's account of a popular mythology, we should ask if the events of the story create their meaning, or did their meaning create the events? It is just this complementarity that the modeling relation allows us to work with. By integrating these levels, the relational theory provides a means for connecting ontology and epistemology, or in more plain terms, source with content. This was applied to material systems as a natural philosophy in Chapter Two, but here it is applied to ethical systems.

In the Vedic tradition, and in similar terms in many other contemplative traditions, one realizes true value, that is, instrumental value aligns with intrinsic value, through the pursuit and coincidence of *jnana* (pursuit of knowledge), *kharma* (understanding of experience), and *bhakti* (devotion to truth). The difficulty, of course, is that wherever true and lasting values may come from we are not certain that we can trust the result which has passed through human subjectivity. While there is no reason why constructed values cannot be 'real' (and they may become so), it is obvious that we also construct them as untested hypotheses. The question then is how will they be tested: in the crucible of social acceptance, through experiments (often personal), or in relation to some revealed truth. Regardless of source, <u>method</u> is therefore important. I suggest that science, social and political process, and religious inquiry may all have valid methods for discovering or constructing value; and relational theory allows such value to reside in both nature and mind, since these are themselves coincident.

Polarization and the "Third Alternative"

Polarization of society along value perspectives can be viewed, in Jung's terms, as a symptom of our split mind. Jung had much to say about such dissociative polarities. He believed that the human mind (perhaps any mind) seeks to be whole, and when faced with a sharp dissociation between unconscious wholeness and conscious separation, the mind attempts to re-integrate itself through various phenomena and behaviors (Jung, 1959). He proposed that humanity in general is experiencing this kind of dissociation and struggle for either advantage or unity. Conflict can thus arise over any misunderstanding of value, either one's own or another's that pits whole and part against one another (the real conflict is not between the parts). The possibilities of a broader harmony thus exist for policy and management only if we can visualize them and learn how they work. Neither intrinsic nor instrumental value is necessarily better. What we may achieve is a balance, which does not exist today.

I suggest, however, that unlike most attempts at social or anthropological synthesis, the relational theory presents a true *third alternative* that is integral and transcendent. The kind of alternative suggested transcends compromise solutions as well. For example, the social anthropologist Ernest Gellner was credited with proposing a *"third option"* that in the end is really a compromise between religion and science, "[coming] *to terms with culture while appreciating science as a more universal form of knowledge and also the need for equally universal forms of polity and morality"* (Rapport, 2000). Gellner identified three sources of purported knowledge in today's society: science, religion, and social relativism; however, he dismissed relativism (which is at the root of postmodern social theory) calling it "laughable" as a source of knowledge, and only appropriate as a description of how we tend to conduct our daily affairs, such as "ordering dinner" or "selecting wallpaper" (Gellner, 1992pg. 95). His main criticism is captured in the following characterization of relativists:

> *"Their insights apply to the decorative rather than the real structural and functional aspects of our life. When they try to apply their insights too far, they constitute a preposterous travesty of the real role of serious knowledge in our lives, and even, for what it is worth, of the actual practice of social science.*

Societies are systems of real constraints, operating in a unique nature, and must be understood as such, and not simply as systems of [relativistic] meaning – even if compulsive meanings do play their (rather variable) role.” (Gellner, 1992 pg. 95)

Relational theory as well, while I argue its value in re-introducing deep meaning, does not then suggest systems of meaning unattached to natural referents: that was its criticism of mechanism. Gellner’s criticism of relativism is thus valid, and I believe it would apply equally to some current theories of policy formation, where there is no appeal to truth—scientific, social, or political—, no natural referent but otherwise requiring a vague faith in discursive symmetry and social process alone.

Although I believe Gellner was too harsh, his discussion is interesting (besides being colorful) precisely because he reduces his picture of knowledge to the kind of essential duality I mentioned above, and then seeks a third option (which he does not believe social relativism provides). However, he did not seem to find it, but only a compromise welding together religious fundamentalism and enlightenment science into a perhaps nightmarish proposal of “constitutional” knowledge. Given the choices of completely unhinged social relativism on the one hand, and Gellner’s fundamentalism on the other, it seems quite sane indeed to seek a third option that is a transcendent, unifying view. Gellner’s “constitutional fundamentalism,” combined the notion of absolute truth on the one hand and absolute method on the other. He claimed that freedom fares better under fundamentalism, both scientific and religious, because both must leave some room for their incompleteness, but he did not fill that space any better than the relativists. Indeed, that middle ground seems like unsteady territory if one is satisfied by neither side alone. Geller was aiming for a substantial view combining both extremes, but that view should be transcendent, not a mere fusion. Also, to exclude the middle ground between experienced and inferred truth, where we might say daily human action and mundane thought take place (social relativism), seems naive no matter how frivolous these activities might seem. Relativism and the options Gellner prefers may each be incapable of representing what is really going on in this domain; it is, after all, the *present* where these supposedly mundane activities occur: Is it not the choice of dinner and wallpaper—the mundane activities of everyday life—that collectively throughout nature add up to our eventual realities?

In relational theory semantic systems are always in relation with realized natural systems. The two are mutually formative and equally effective; and it is only their combination that constitutes an implicit truth. Gellner reified the past in terms of established truths and methods of discovery, but overlooked the present where meanings are actively making their determination, for better or for worse. In this sense social construction is not entirely relative and it can indeed connect with scientific and religious 'reality.' Yet the mundane and uninformed ramblings of human thought are not what can constitute transcendent awareness. We can say they have effect, but our awareness of their effect is another matter. How different thoughts and actions work to their own ends, and how they can be supervened is the transcendence my *third option* refers to. It is not relativist truth, it is relational truth. It is not determined truth; it is in the process of determining truth. It is not unifying in mechanistic terms as a new form of energy or physical field (e.g. Sheldrake, 1991), but it is informational. It is a natural link between semantics and syntax in all systems. Such transcendence resolves conflict by entering a level of interaction where the differences fueling conflict become two essential ingredients comprising a new reality, and thus where forces for their mutual destruction are replaced with a need for their mutual preservation.

Integral Solutions

The basic duality of *experienced* vs. *inferred* knowledge prior to a transcendent option generally associates with the distinction between *intrinsic* and *instrumental* value. **Figure V-6** shows these values as alternatives that might constitute an integral whole. Their respective shaping of environmental or ecosystemic use and management practice leads to different sets of good and bad implications for ecosystems (the ascending arrows). These alternatives seem to define a basic duality as discussed above, and the timing may be right for their integration.

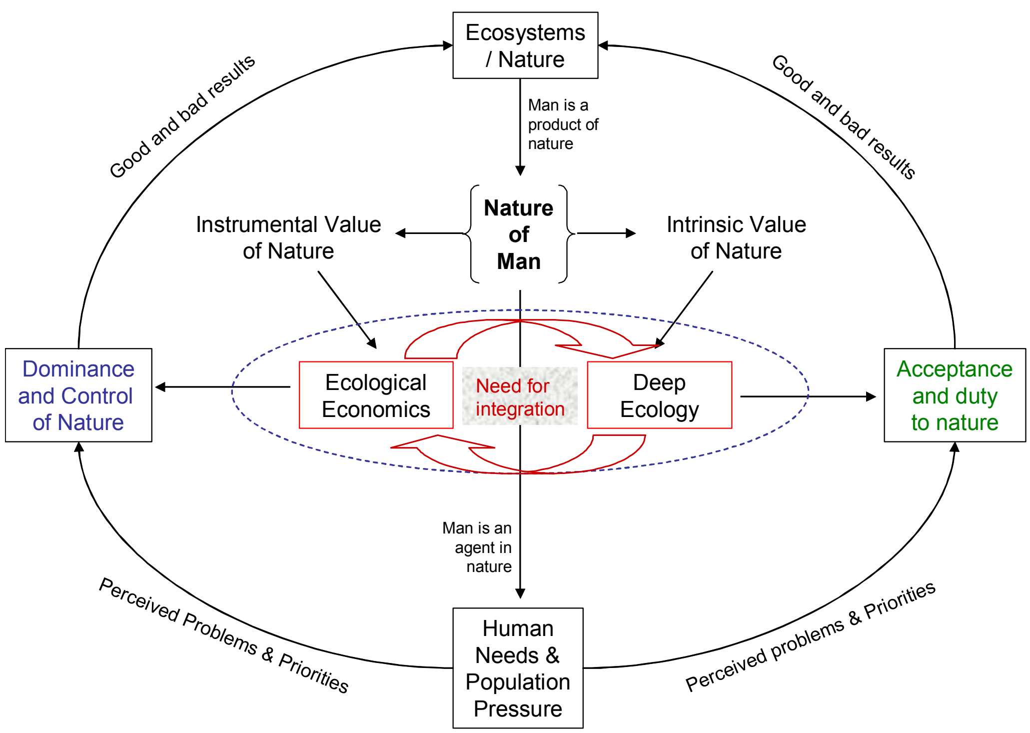

Figure V-6: Integrating Instrumental and Intrinsic Values

In particular, today, as we over- or under-emphasize the values on either side of this divide, we then contend with the effects from the other side, both material and psychological. If Jung was correct, this phenomenon is each half of reality asserting itself, attempting to balance the whole within the collective thoughts of Mankind. It seems true that none of the cultures on either side of this diagram have the whole solution worked out: They are each capable of the best and worst of environmental management. We are faced with the dilemma: Should we not change Nature that is already perfect, or can the changes we make also be part of that perfection? It seems that when only one side of this diagram is represented in policy and action, that is most catastrophic; for then we either do not hold enough respect for nature or do not recognize our legitimate role in it.

In the diagram neither the instrumental nor the intrinsic value system is superior, but instead they are brought into relationship where, hopefully, the benefits of each can be maximized. The "Nature of Man," as represented, occupies that middle ground discussed above, where we are integral as part of nature and yet split psychologically between essentially syntactic and semantic perspectives in need of integration. We may legitimately ask if a culture limited by mechanistic thought might be missing the heart of ethical thought and thus might indeed be as destructive as many claim, where dissatisfaction triggers larger changes rather than smaller ones, to the point of risking annihilation; what some claim industrial society is now doing. From the other side we may ask if a system of unentailed meaning, even deep meaning, is sufficient to meet human needs without its connection to, and reflection in, the material world, and thus where the only escape from human misery is the renunciation of life itself; a failing that may be found in some Eastern philosophies. These are indeed opposite pathologies that seem to define our moral dilemma. Relational complexity can at least begin to ask how these two halves of the picture are related; how they can inform and balance each other. The diagram itself defines a modeling relation comprised of relations that run deep in both scientific philosophy and mystical experience, but that are not openly, or often willingly, connected.

Vedic followers contend that materialistic thought alone is incapable of providing values that would guide us to true sustainability because it is too narrow to embrace nature's complexity—a claim that is supported by relational theory (Kineman, 2005; Kineman and Kumar, 2007). And yet it is materially productive, allowing it to take root in human practice. Perhaps the archetypical duality can be expressed in terms of *being* and *doing*. Good policy and effective management, as well as a healthy life, would seem to involve both in equal measure. Intrinsic value, or the value *in* nature or existence, is expressed in many cultures as traditional wisdom that comes from a long and remembered connection with nature through social instruments such as councils of elders, shamans, gurus, priests, ministers, and common people with an uncommon view. Those with a deep understanding of inner or transpersonal experience (e.g., Wilbur, 1986) in any culture cannot be excluded. It is certain that direct experience on many levels has much to inform science and religion, and that could be represented in a relational model. Perhaps the diagram suggests an analogy to the two hemispheres of the mammalian brain, where a connection between halves, like the *corpus callosum*, is needed to allow them to function as a unit while performing fundamentally different kinds of logic. A new transcendent approach to nature might have as its primary goal to re-assemble this fractured reality.

Conclusion

The strongest message of the relational theory is that functions that exist in nature and that are reflected in ‘minds’ (to whatever extent complex systems can be said to develop minds, metaphorically or otherwise), are in mutual causal relationship with material reality at three levels: efficient levels involving actual changes to the structure of systems, formal levels involving abstract patterns ‘copied’ from and into nature, or 'mimicked' in nature, and final levels, involving anticipated futures that through the first two causalities, become real over time. The foundation of the relational theory is not limited to human experience, or to living systems, but applies as a fundamental and general reality concept underlying all natural systems. The case of mechanism is a special case, but one that cannot be called ‘unnatural’ because it is not only a logical consequence of reduction, but an experienced one as well. But just the same, relational components, despite their complex uncertainties, are as natural and empirical; for they are ontological phenomena drawn into the world of living experience, and perhaps responsible for experience itself.

As we consider the application and implication of this philosophy and its corresponding theory to various aspects of human experience, a principle of communication emerges. As systems ‘inform’ each other (which may be thought of as ‘forming’ aspects of each other), they do so by means that are knowable as structure and function in complex relationship. It is the case, therefore, that mental models within nature and in the human constructs of science, policy, society, and ethics, are not inert models or meaningless abstractions, nor are they subjectivities without effect. In the human case we create them specifically because we believe they will have effects and that they will change our conditions. They do; but often not under our control. All models, if they can exist in a natural system, are, in accordance with relational theory, in communication with other natural systems. They write their message into the material form of the environment and other systems more or less automatically (I would prefer to say naturally), and yet through behavior, as behavior reflects belief.

We can see these principles quite clearly in Ecology and reflected on the landscape. If, for example, we look at a satellite image of the USA-Mexico border we will see a major land cover difference across the sharp line that defines the border. This is today a structural difference on the landscape, but it began as a functional difference in ideological, political, ethical, and economic systems. What was believed was acted on as a natural consequence of that belief, and those actions 'wrote' the message of those beliefs on the landscape (see Turner, 1990). Today new generations of humans are born into that difference. They inadvertently 'read' and incorporate its message. Not only humans but also fauna and flora 'read' that message, encoding it into their models and behaviors; an obvious consequence of accommodation, adaptation and evolution. The message thus propagates and its value is tested throughout nature. In the same manner, there is a response where new functions resulting from the encodings we initiated, return our message in the form of natural consequences. The "collective unconscious" that Jung described, which stores our deepest convictions, thus produces a collective reality that we must then live in.

As a simple analogy, flying over the agricultural landscape of most developed countries one will see primarily Cartesian patterns—circles and squares resulting from two kinds of irrigation system. Other linear features connect the grey spread of human settlements. Natural areas are fragmented into separately defined units with fixed geography, where species and habitats cannot move in response to climate or other changes, thus hastening their end. Monocultures appear over vast areas where diverse self-managed systems were before. Great herds that once roamed the plains no longer exist, and could not exist in this Cartesian jungle. The great forests, in which at one time it was said that a squirrel could travel from the Atlantic ocean to the Mississippi river without ever touching the ground (Eckert, 1967), are now a patchwork with little or no connectivity. We have been writing the message of mechanism into nature and into our future at an accelerating pace. The same message is written into our human environments: the structure and function of cities, offices, homes, parks, transportation systems, and entertainment establishments. Would it make a difference if we were to develop a natural philosophy based on the message of relational complexity? Might we recognize, not just individually but also culturally and scientifically, the therapeutic role of artistic expression, inner experience, and contact with evolved nature? In the new field of Art Therapy (Edwards, 2004; Campanelli and Kaplan, 1996), the power of natural artistic expression to heal the fractured mind is being demonstrated. Does this not also apply to our new digital global 'mind'(Berners-Lee, 1999) if it does not escape construction in the image of a machine (Wright, 1997)?

I do not wish to trivialize these issues by reducing them to information models. However I believe change must begin with our most basic concept of information and nature, as discussed in these pages, to achieve the kind of scientific, political, social, and ethical convergence these analogies suggest and the assessments call for. That change, at its core, involves incorporating functions and their meanings into what is today primarily data syntax (the arguments of Chapter Two, Three, and Four). To put it another way, the means by which we inform ourselves as a society must be capable of communicating deep and self-entailed aspects of living systems—how we and other complex systems function—not just the facts and figures of present and past behavior that cannot be interpreted without their original meanings. Thus while our new brain may someday be able to think, that is, we may achieve the vision of superimposing a “Semantic Web” on top of our present “Syntactic Web,” there remains the question of what such a ‘brain’ will have to think about. Knowledge of reality, as we have seen, comes from many sources that we may call natural and human, and it is both constructed and discovered. We cannot do without either source or either process. . Relational Informatics, as a feasible application of that theory, may provide a powerful tool for creative human progress.

I believe its development is the way to reduce random or intentional substitution of interpretive contexts that are at the root of misunderstanding about the complexities of the environment and ecosystem, and thus the polarization and conflict we see today over environmental issues. Relational theory tells us that original, natural function and context, and thus meaning, cannot be recovered (except from personal experience, or expertise), once separated from its original source. It is thus important to record and entail such information within the informatics as close to its original discovery as possible; especially because we increasingly do not trust experts to carry these semantics, nor can we relay on separate publications for unambiguous interpretation. I thus envision the new informatics providing a commonly reviewed and accessible environment linking structure, function, and context in highly complex ways, which I believe is the minimum requirement for producing a ‘Knowledge’ Web that might communicate with and inform policy and decision making. Before we can improve priorities for Environmental and Ecosystem Management we must improve information, recognizing that neither information nor knowledge are mere aggregations of data.

If we rise to this challenge, we may indeed begin to write more of the natural, organic and complex messages and signatures into our built and managed world, keeping us (and the rest of nature) informed of and in contact with realities we do not conjure ourselves on short notice. Will this help heal the ‘split mind’ of Humanity? Peter Russell wrote, *“The image a society has of itself can play a crucial role in the shaping of its future. A positive vision is like the light at the end of the tunnel, which, even though dimly glimpsed, encourages us to step in that direction.”* (Russell, 1983) Bela H. Banathy expressed a similar hopeful sentiment for “guided evolution,” where the images we form of nature and ourselves, if they themselves are well-informed, can guide us in positive and healthy directions as a society (Banathy, 2000).

I believe we could make a very big improvement in the management of ecosystems and our interactions with them by exploring the relational concept of information and nature, for this will not only change how we study nature, but it will change attitudes towards nature in ways that may better balance human values. As we change the formalisms by which we describe and manage nature, and by which we live, we will find our new concepts returned to us through our surroundings. Perhaps where we have inadvertently scribbled the message “non-living mechanism,” we may more carefully draw another message: “life and complexity.”

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