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Viewpoint

The nature of ecological complexity: A protocol for building the narrative

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ABSTRACT

We show that a realist view of ecology does not pay sufficient attention to the role of the observer dealing with complex systems. Complexity after Rosen [Rosen, R., 2000. Essays on Life Itself. Columbia University Press, New York, p. 257] is something that cannot be modeled. Conventional properties ascribed to complex systems are in fact prescriptions for what it takes to make a complex system yield to a model structure, to make it a simple system, albeit a complicated one. Complexity is not a material property, but turns rather on the question that is posed. It is normative to the degree that complexity arises from the lack of a paradigm, lack of an accepted set of modeling assertions. We develop a scheme for making complexity tractable. Our protocol arises from Pattee [Pattee, H., 1978. The complementarity principle in biological and social structures. J. Soc. Biol. Struct. 1, 191–200] laws and rules, Allen and Hoekstra [Allen, T.F.H., Hoekstra, T.W., 1992. Toward a Unified Ecology. University of Columbia Press, New York] scale versus type, observation protocol versus observed structure and Rosen [Rosen, R. 2000. Essays on Life Itself. Columbia University Press, New York, p. 257] essence versus realization. In a pair of cycles, one reinforces patterns of model building, and the cycle of the other deals with the changes that appear in the essence of that which is modeled. We use narrative to rise above the local constraints of models. In the end, we give an application in a salmon fishery as we build a narrative from a set of separate models.

1. Introduction

The issue of complexity has an intuitive appeal that invites informal treatments from those who feel they study complex situations. Proficiency in some special field that deals with elaborate entities, such as ecosystems, does not necessarily make the local expert competent in a discussion of complexity, even within the field wherein the expertise lies. Being adept in mathematical expression of ecological systems also is no guarantee of an adequate understanding of the issue. Their lack of proficiency notwithstanding, many ecologists give complexity a go anyway. This paper will identify where informal treatments of complexity go wrong, and through application to issues of sustainability, it will show how the well developed science of complexity can indeed offer something new and substantial to ecology. Narrative is the key to dealing with complexity without compromise.

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2. Views of complexity

The philosophical posture most commonly taken by newcomers to the discussion of complexity is empiricist in a way that invokes metaphysics over epistemology (Ahl and Allen, 1996; Allen et al., 2001). Using that philosophical posture, complexity is taken to be an issue beyond the observer, where some material situations are complex while others are not. Complexity is therefore, in this view, something to be found as an externality, something to be discovered. More sophisticated views may invoke a duality between the observer and the observed. An observed is taken as having an identity that may be observed. The problem is that despite its name, an observed is usually taken to apply above and beyond observation. For someone satisfied with using the concept of "the observed," the falling tree does make a noise even if nobody is there to hear it. The notion of an observed, in complexity, is therefore a metaphysical notion, not the strictly epistemological device that we would prefer.

The authors here choose to use the notion of *the other*, a device used under constructivist philosophies (Allen et al., 2001; Piaget, 1963). The other, as we use it, is indeed strictly epistemological and is part of observation, but is that part which arises above and beyond the choices and decisions of the observer. Commonly, the other is a matter of dynamics: one chooses to study lions with regard to their spatial position, but one still does not get to say where the animals will go. The movement of the lions resides in the other. But the things in the other are not only undefined, they are undefinable. We need special devices to deal with the other.

Our ultimate device for dealing with complexity and the other is narrative. A realist of an empiricist bent might say that the lions move in reality; in our view they may or may not, because we are not sure what moving in reality means. Movement does appear to be part of what we see, but there is nothing necessary about its appearance. In contrast to the realist view that often underlies lay accounts of complexity, we remain agnostic about external reality. We favor a philosophy, where the observer's knowledge and understanding is constructed by interaction with experience (Piaget, 1963). The experience is laid out in a narrative. Narratives are not about the verity of a situation, but are rather an explicit statement of what the narrator views as important. Early parts of the narrative open the opportunity to see meaning in later parts of the story. A tenet of modernist, as opposed to post-modern, science is that improvement in scientific insight approaches reality. That view is held stridently because it is one of the central myths of modernist science. As such it motivates and disciplines modernist scientists but, as with all myths, its usefulness does not turn on the myth being true in a literal sense. Myth is a device that works when logic and consistency break down. Certainly, reason and consistency do play a central role in the conduct of science, and that is indeed one of the strengths of the whole endeavor. But in the end, complexity moves out beyond logic and consistency, and so it requires a new scientific posture.

The lay view of complexity identifies that complex systems have: many parts; many types of relationships between many types of part; emergence of new structure de novo; poor predictability; non-linear behavior to the point of chaos. But if complexity is to be a material issue, then the above characteristics take on a muddled meaning. The problem is that nature does not prescribe systems for the scientist; rather the scientist must take responsibility for definitions and boundaries. Some decisions as to these matters are more useful than others, but none are prescribed for the investigator by nature. If it is the decision of the observer that determines what is complex about a system, then complexity must be a normative, rather than material, issue.

Number of parts may be mistaken as part of the material basis of complexity. The mistake is that parts, and therefore the number of them, come from observer decisions as to what constitutes the whole, and how those components comprise it. The number of types of parts again is a matter of distinctions made by the observer, who had better take responsibility for them, rather than abdicating to nature in some mysterious way. Emergence is also seen as part of complexity, as new structures, behaviors and organizations arise. Unfortunately, this too is a matter of observer decision. It depends on the definitions as to what changes constitute a new structure (emergence) as opposed to changes that amount to merely a new state of some old structure (behavior). Emergence will often follow similar patterns, as when hot moist air leads to thunderheads. But even with experience, emergent behavior is hard to predict, because details too fine to be known fix the outcome with great specificity. There is no simple prescription for identifying what will be part of the general pattern and what will be specific, because so much turns on decisions in bounding the system. With all this depending on observer decisions, complexity as a material matter is in trouble.

Some of these same issues of complexity and materiality arise from asserting that non-linearity is a property of complex systems. Linking complexity and non-linearity too tightly displays a naiveté as to what is a model. The world is neither linear nor non-linear in and of itself. Neither is the world chaotic or otherwise, it is rather that some situations appear to yield to a chaotic model to a satisfactory degree, and others do not. What is satisfactory again falls to the observer. Chaos, as with most mathematics in ecology, is a matter of metaphor (for an accessible account of chaos theory, see Gleick, 1988). Even if some known equation and chaotic strange attractor is found to fit, this does not say that the world in itself is chaotic.

In an example of mistaking number of parts as a basis for complexity, the empiricist realist view would insist that the brain is complex, because it has billions of neurons that are responsible for cognition. While true as to the facts, this is not necessarily so as to implications. For questions about the neurological basis of thought, there are indeed billions of neurons. However, there are other questions that might be of interest where such facts are beside the point. An example of the number of neurons being irrelevant is severe epilepsy, where one radical solution is to sever the *corpus callosum* so as to stop the amplifying feedbacks between the cerebral hemispheres. The model for that procedure is a brain consisting of just two parts, the halves. A brain seen as having just two parts that matter is specified as a very simple system. The authors' view of complexity is that it is not a matter of nature, but of lack of consensus on some critical distinctions. Simplicity, and so also complexity are normative matters. This point was not properly understood in an evening discussion on complexity at the 2002 Ecological Society of America meeting in Tucson. In a twist of irony, not lost on complexity specialists in the room, there was a suggestion from the realist camp for a show of hands that the brain was indeed complex.

To assert that the brain is complex because in reality it has billions of neurons is to miss the point, and displays a misunderstanding of how science works. Data collection in significant detail is at the center of the scientific endeavor. However, science does not attempt a full catalogue because, first, that is impossible to achieve, and second, if it were possible, the data would be as unmanageable as the material externality. The point of models is to make simplifying assumptions explicit. With the light of a model shone upon them, the consequences of making those assumptions can be tested. No assumptions are strictly ultimately true, so the quest is not for a verity, but is rather for premises that still allow prediction. Science is about finding out which untruths can be asserted so as to make the system tractable, while still achieving an adequate account of what will appear (Allen, 2002). Science is thus a process of throwing things out for particular purposes, and is precisely not a matter of insisting on all the details. We need details, but we seek the minimal set. If a fact does not pertain to the question, it falls outside the discourse. The fact that there are billions of neurons in the human brain does not contribute to an understanding of the successful treatment of epilepsy by surgery.

Instead of going for complex materiality, we assert that complexity is normative, something that is identified by an agreement. Complexity is the ultimate semantic argument. If one has a paradigm, then the system is simple; perhaps complicated (Allen et al., 2003a), but still simple rather than complex. If one does not have a paradigm for it, then the system is complex. Paradigms are essential for science, and are in a sense the end product of it. They inform scientists as to how to look at the world in a way that has currency and relevance. Kuhn (1962) identifies that paradigms represent agreements as to what is significant, what are useful tools and what falls within accepted vocabulary (competing paradigms are pejoratively accused of using jargon). In negative, but still insightful terms, a paradigm is a tacit agreement not to ask certain questions. Paradigms tell their adherents how to address certain aspects of experience of the world as it is observed. Complexity, then, arises when there is no paradigm, when critical decisions are left unmade. The properties that are generally understood by lay and many expert investigators as leading to complexity come from asserting coherent intellectual and operational frame of reference in a paradigm. Paradigms are normative frameworks that are a requirement for orderly development of scientific thought. Being the very antithesis of a paradigm, complexity cannot be understood without reference to normative values, whereupon the complexity is lost to us.

3. How to study complexity

The point of studying complexity is to turn it into something simple. A system is simple when the observer has decided on the following distinctions. What is: structure versus behavior; rate-independent versus rate-dependent; meaningful change versus mere dynamics; discrete versus continuous? (Ahl and Allen, 1996; Pattee, 1978) The matter of continuity identifies what can be usefully quantified as opposed to raised to the level of a qualitative distinction. The hallmark of complexity is organization. While piles of sand are addressed by complexity scientists, there is something wanting as to the complexity of something with such little organization. We suppose that sand pile investigators (Bak et al., 1987) are after the minimal case. By getting a handle on the organization behind complexity, we make it simple.

The authors here have asserted elsewhere (Allen et al., 1999; McCormick et al., 2004) measurable characteristics of what makes something complex. We now recant that error. We contended that complex systems are deeply hierarchical, the deeper the hierarchy the more complex they are. Complexity in those terms displays many levels of constraint. The constraints, we said, are linked with explicit aggregation criteria. We continued by asserting that complexity invites links between large and small scale, and between fast and slow processes. Complex systems have explicit links between multiple types, or equivalency classes (McCormick et al., 2004). To deal with a complex system it must be assigned to an explicit type, and be given an unequivocal boundary. In all this, at a fundamental level, we were wrong. But now, in the light of our desire to define complexity as something normative, we see a striking reversal of what is simple as opposed to complex.

The above characteristics that we used to define complexity are in fact what one does to a system that is undefined so that it can be assigned to the class of simple things. In a sense this turns the standard expert approach to hierarchy and complexity on its head. The characteristics that are normally assigned to something complex are in fact how one makes it simple (Fig. 1). Ironically, the standard definitions of complexity are in fact characteristics of a system that has been defined into simplicity. In return for our sacrifice, this turnaround gives us something, that is operational when complexity itself blunts other lines of attack. It is this relationship to simplicity, more than any other reason, that demands a sophisticated epistemology going beyond realist, metaphysical assertions as to material nature and external reality. Before simplicity there is complexity, and the characteristics that we mistook for complexity heretofore are in fact descriptions of systems made simple. A telling observation in computer science and artificial intelligence (AI) is that, once it works, it is not AI anymore. Once complexity is made workable, it is no longer complex. The characteristics conventionally ascribed to complexity are precisely not about complexity per se.

Sometimes a system exhibits a non-linearity that is severe enough for the system to exhibit emergence and instability. This happens as the curve folds back on itself to make a pleat. Instability arises as the state of the system moves in freefall over the edge of the fold. The instability causes emergence of a new situation constrained by new limitations. Using the

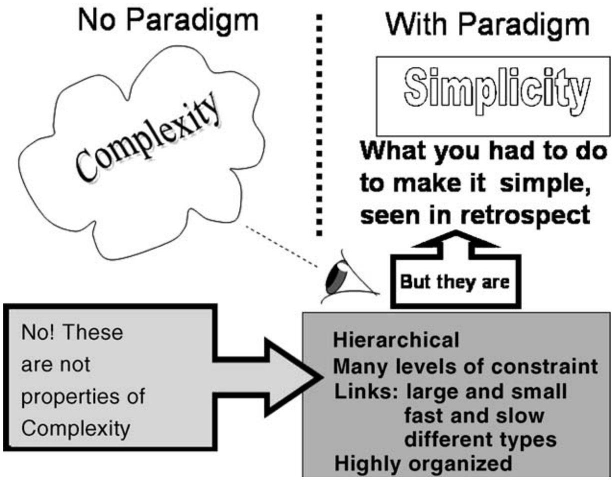

Fig. 1 – Complexity is a matter of not having a paradigm. The properties assigned to complex systems by lay and expert opinion alike are no such thing. They are what you do to make a system simple.

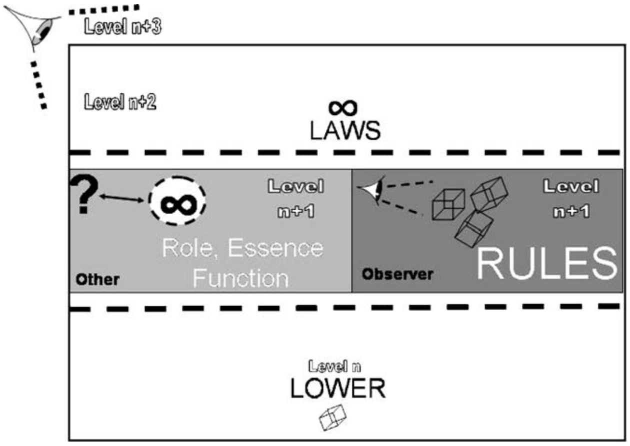

Fig. 2 – The outline of the scheme for dealing with complexity. At the top level is the meta-observer who sets the arena of discourse. The laws (after Pattee, 1978) are pure dynamics and so are infinite. The rules are, however finite, being an open decision set as to structural equivalence classes. On the side of the other, there is the role, essence or relational function. While these represent bounds, there is an infinite number of ways to fill a role, so that the role is a bounded infinity, as is a strange attractor in chaos theory. At the bottom of the figure at level *n* is the observed structure. Note that it lies in the decisions of the observer while also applying to the other.

example of liquefaction in gasses, Rosen (1989) notes the sudden imposition of new, tighter constraints on particles as the liquid forms. He suggests a protocol for dealing with these situations, which normalizes away the fold, so a new well-behaved account appears. Behavior between the sides of the fold cannot be modeled and are so complex according to Rosen (2000). By taking the strong non-linearity, the fold, out of the system, Rosen has made a complex system simple, and all according to the normative definitions of complexity that we recommend. The rest of this paper lays out a procedure of our own that shows how to address complexity.

4. A new general method

We have defined complexity in terms of a constructivist frame that recognizes the critical role of the observer; it is now time to operationalize this post-modern view to solve complex problems in ecology and sustainability. Elsewhere (see McCormick et al., 2004; Allen et al., 2005) the authors here have developed a scheme that aims to make solving complex problems in ecology a practical matter. The scheme turns on defining a set of contexts. Within that complex of constraints, we create a pair of cycles, one that checks the model against observed structures and another that acknowledges the constant change of the context and its embedded structures, which appear as observables.

We derived the scheme by uniting many ideas published elsewhere by ourselves and others. Pattee (1978) made the distinction between laws and rules. Laws are dynamical, structure-independent, rate-dependent, inexorable and universal. They indicate the universals that apply within the arena of discourse. Laws in Pattee's terms are not the vernacular laws of nature, whose ownership is sometimes staked out by physics. Most laws in physics are a matter of what is possible, expressed as relative rates and so the vernacular meaning of law of nature is a subset of Pattee's special usage of laws. Above the laws, we insert a meta-observer who chooses the discourse, and so there are laws according to Pattee in biology that are clearly not laws of physics. When dealing with complexity, it is most helpful to bound the system explicitly. Laws are an expression of possibilities within a chosen, bounded discourse (Fig. 2).

As a counterpart to laws, Pattee raises the idea of rules. The latter define the subset, within what is possible, that is in fact allowed. There are many things in physics, such as superconductivity, that are possible but which never apply to biology because they are not allowed inside what biologists decide is biological. Rules are the observers' contribution to what is observed, that which arises because of explicit observer decisions. They are local, arbitrary, rate-independent and structure-dependent. Since rules offer limits chosen by the observer, they define the models of the biologist. Underpinning any model is an equivalence class (Rosen, 2000). At a trivial level, it is giving something a name. These are categories invented so that observed entities may be assigned to classes. The model becomes the rules for equivalence (Fig. 2). The point of science is to find the basis of the equivalence in observed entities, the reason for the patterns we recognize.

The basis of the equivalence is found in the material context of the thing in question. One cannot have direct access to that context, but one can infer it as patterns appear in observations. Various systems scientists have made reference to these contexts, naming them as either roles (Bailey, 1990) or relational functions (Simon, 1962). Equivalent to role and relational function is Rosen's (2000) notion of ''essence.'' This term is useful in its implications of something that cannot be defined, but is nevertheless involved. It is, however, unfortunate that essence also comes with a lot of baggage about essences being concretely real in some way, independent of observer decisions. While unknowable in any direct way, Plato's shadows on the wall of the cave do imply that making the shadows is something real, which is independent of the one in the cave looking at the wall. If we dissect away and reject this latter implication, then essence is a powerful idea. We need essence to be undefinable and not directly knowable, but it should be involved in what we do know. While inspired by his original idea, we are not prepared to carry Plato's realist baggage.

Let us clarify the notion of essence so it can be seen to resemble a role, Bailey's (1990) term. Essences become realized. In biology it might be an organism that is the realization of a species. The realized organism belongs to a species. In social systems, the essence might be the presidency of the United States, where an individual president is one of its realizations. The equivalence class on the side of the observer might be the list of all past presidents, a finite and defined set. In contrast to the full list, both species and the presidency cannot be defined, because they are constantly changing as they mutate. For instance, Richard Nixon's Watergate scandal clearly changed the presidency, whereupon Jimmy Carter was its next elected realization. The essence is mutable. However, it depends heavily on the level of analysis in the equivalence class. Whereas the mutability arises in the other, the level of analysis to which any given essence is tied is restricted to the side of the observer. Level of analysis is excluded from the other, although it is responsible for the reference for the essence on the observer side.

If the essence behind dogs is dogginess, then it depends on the equivalence class of dogs and dog-like creatures to which it pertains. A particular dog may be assigned to a class of dogs, but there are many criteria that could be used for inclusion in that class. For instance, would wolves be potential members of the class. If so, then the essence of dogginess would not be the species *Canis domesticus*. Alternatively, hyenas hunt like dogs, but are 25 million years more closely related to true cats than they are to dogs. Hyenas are on the cat not the dog side of the Carnivora. And yet hyenas hunt in packs like dogs, and a lay person could easily mistake them for actual dogs.

Even further away on the evolutionary tree are the thylacines, otherwise called Tasmanian tigers, extinct only in the 20th century. Pictures of it show it to be some sort of marsupial dog-like creature. The essence of dogginess could certainly apply here. Had Australian Aboriginals instead of Europeans culturally exploded over the world, we might think of "thylacinty" instead of dogginess. At a low level of analysis, "thylacinty" would amount to the species *Thylacinus cynocephalus* but at the general level of analysis it would indeed be the same thing as dogginess. Note it is the criteria for inclusion in the equivalence set that matters. From the evolutionary convergence we see in dogs, hyenas and thylacines, there appears to be a stable configuration of characteristics that represents one way of being a carnivorous mammal: non-retractable claws, moderate sized canine teeth for harassing not saber tooth, run the prey down, usually with a pack. If we look at the paws of a cheetah, they look like dog paws, because the "claws" are non-retractable, protecting the foot and giving a footing in the chase, which is fast and long for a cat. There is a touch of dogginess to cheetahs, their clear status as a big cat notwithstanding.

So essence is undefinable, although it is linked to definitions that fix the level of analysis. Essence is the cause of the pattern that we see in an equivalence class, of say dogs. Even so, it does not exist independent of a human decision scheme that defines the problem at hand. We have thus dissected the crude realism of Plato's shadows on the cave wall away from Rosen's and our meaning of essence.

The scheme, in which we will do our best to link the undefinables on the side of the other to classes on the side of the observer, depends crucially on the observed structure. The lowest level, n, is held in the context of the meta-observer at level $n+3$, the laws at level $n+2$ and the rules and material contexts both occurring at level $n+1$. With regard to the material context, Bailey (1990) couples roles at level $n+1$ to incumbents, which lie at the observable level n. Bailey is a social scientist. This might invoke the notion of the US presidency versus a president in the preceding discussion of essence. Rosen (2000) couples essences with realizations of essences, as when an organism is a realization of some incalculable that lies behind the pattern of some class. Finally, Simon (1962) speaks of organized structures as corresponding to relational functions. The relational functions link an organized structure to its context. All these notions apply at level $n+1$, on the side of the other (Fig. 2).

At the level of observables, level n, one sees entities. Observables appear on the side of the observer, where decisions of the observer pertain. However, observables also exist in aspects of the other, where we find aspects of observation above and beyond observer decisions. Note we do not ascribe the structure to the status of an observed that exists independent of observation. The reason we take this position is that as scientists we are bound by observation and epistemology over metaphysics. There may well be metaphysical implications to science, but one cannot operationalize them in day to day scientific activity.

The beginning of our process is to have an experience, and the end product of one part of our protocol is a model. At first there may well not be recognition of what experience is or what it might represent. But then one gives the entity a name and our process is in motion. A name amounts to an assignment of the observable to an equivalence class. The class generalizes the particulars that have been seen, putting them in an intellectual context. Equivalence classes relate observables to their context, which is exactly what models are supposed to do. Equivalence classes are models. Once the entity has been assigned to a class it is then incumbent on the scientist to verify that it does indeed belong in the class. This act closes the loop of model building: assignment to a class and verification of membership. Models invoke a linguistic coding, making the cycle of model building a linguistic, structure-based cycle. Models develop in discrete semiotic steps by going round the loop in an iterative fashion that fine tunes meaning and adjusts to changes (Fig. 3).

One time around the modeling loop defines the significance of the entity at a structural level, and sets the stage for the measurement phase of an investigation. Structure being recognized, the scientist is in a position to formalize measurement. This is achieved by invoking scale and type. There are two considerations here that pertain to both scale and type. First they both apply in principle as the equivalence class is defined. Scale and type also apply, but in a different way, to the observed entity. For instance, while organism as a type is independent of scale, a particular organism does appear at a particular size. Allen and Hoekstra (1992) organize their treatment of ecology at large around the distinction between scale versus type. Scale applies to the size and longevity of an observed structure, but it is also relevant to the grain and extent of observation protocols even before there has been any formal observation in which the observed structure might have been found. Grain determines the smallest distinction in time and space made in an observation scheme, while extent reflects the scope of the universe within which a set of observations is made. Type pertains to an observation protocol that sets a class of entity that one might use as a search image, for instance the type of ecological thing that we agree to call organism. As a slightly different issue, observed entities belong to a type. Scale and type are at the core of measurement.

The beauty of the observed entity is that it sits on both sides of the observer/other distinction, facilitating a means of understanding beyond observer assignations. What is observed and measured also exists in a context external to the decisions of the observer. The contextual level above any structure gives it meaning, as when the heart is meaningfully seen as a pump. In a model, there is an observer-designated context, which gives modeled entities meaning. A main point of science is to link observables to the context in the other. Achieving this linkage starts with the meaning assigned by the observer to the observable in the model. The linkage to context on the side of the other gives a more general place to the meaning in the model. But we must hasten to add that we do not want to assert there is meaning in and of itself in an external material world on the side of the other. Humans create the meaning. We may see a leaf as being flat because it is the means of production for the plant that needs a large area for exchange, but the plant in itself does not care, it has no sense of value. Ecosystems and thunderheads do not care about the role they play, or that they give meaning to their parts in the human psyche.

Much as there is a cycle of model building and adjustment, there is a cycle in the other. The cycle on the side of the other is one of realization and reinforcement. This is a cycle of adjusting dynamics (Fig. 3). Koestler (1967) spoke of the self-assertion of parts, as when cancer cells assert themselves over their host. Thus, parts are given meaning by the whole while also influencing it. This influence corresponds to the reinforcement part of the material cycle, as when we referred to presidents being realized in elections, while themselves influencing the presidency. In biological systems, the organism reproduces, and thus influences its deme and species through natural selection. DNA then realizes the next organism in the completion of the cycle. As the cycle of reinforcement and realization moves through the realized structure, it becomes possible to make a link across to the modeling cycle.

The scheme we have presented here is related to Rosen's notion (1991) of formal models and entailment. Formal models are neither right nor wrong, so long as what they posit follows logically. Formal models usually consist of a set of scaling rules, like the laws of aerodynamics, and so are themselves scale-independent. In fact, the utility of representing something in models is in being able to assert that everything is

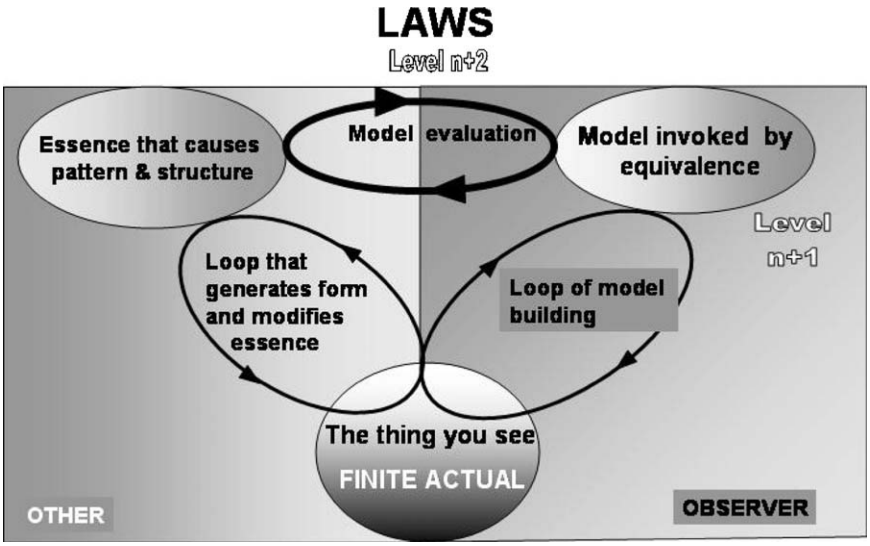

Fig. 3 – An extension of Fig. 2. Here, the processes of assignment to class and verification of membership occurs as a loop of model updating. Once around that loop and then formal scaling and typing can be imposed. On the side of the other, the same lower level structure arises as a realization of the role, essence or relational function. The structure in the material system reciprocates by changing the nature of the role or context at level *n* + 1. The cycle on the modeling side is semiotic and invokes changes in representation. It is a linguistic cycle. The cycle on the side of the other adjusts dynamics. The cycle across the top is a process of evaluation of the model that links the model to the upper level in the other. The model is structural and the other is dynamic, and this difference leads to complementarities, equivalent to the wave particle duality in physics.

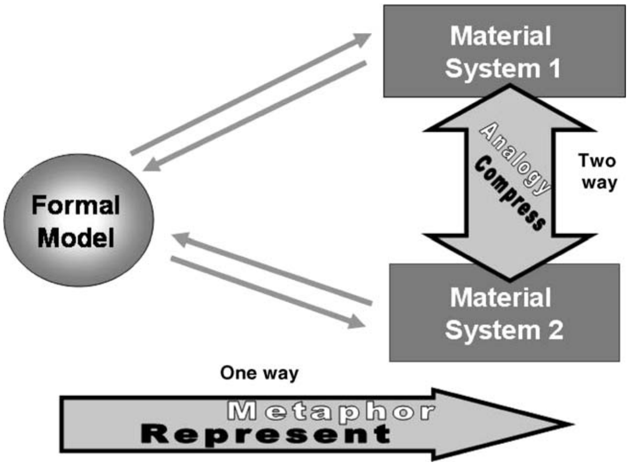

Fig. 4 – A formal model is a set of scaling equations that are therefore as a group scale-independent. If it is possible to encode two material systems into and decode them out of the formal model, then the two material systems become analog models of each other. A paper dart and a DC 10 can be models of each other. If the dart were a toy scaled model of a DC 10, then the big plane would clearly be the model for the small one, so it really does work both ways. Experimentation depends on these principles, where the experimental situation is cast as an analogue of the system of interest. The model is a representation of the observed systems. The equivalence across the two analog systems is a compression down to only what is equivalent (after Rosen, 1991).

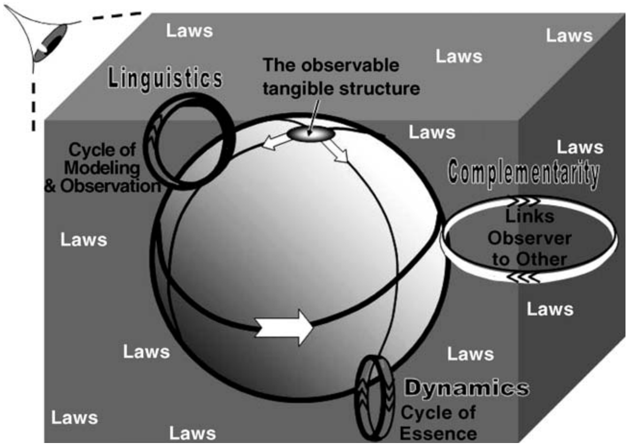

Fig. 5 – A respecification of Fig. 2 so as to de-emphasize the level-based structure. The two cycles now pass through the observed structure at level n, which is now put at the north pole of a sphere. The linguistic modeling cycle passes at ninety degrees through the pole relative to the dynamical cycle, which modifies the role, context or essence of the observed structure. The two longitudinal cycles connect in the observed structure, but cycle through different sides of the contextual level *n* + 1. The attempt to join them is itself a cycle at the equator of the globe, and it invokes a complementarity. This figure shows the unity of the scheme.

equivalent except scale. Of course everything is not equivalent, but that is where assumptions come into the discourse. Two material observables may both encode into and decode from a single formal model. This coincidence opens the door to the two material systems being recognized as analog models of each other (Fig. 4). In an analogy, certain features of the analogs appear to be shared. The analogy is a compression down to only what is equivalent between to observables. The model relates to observables by a process of decoding into the world of observation. The point of all this encoding and decoding is an attempt to link the causal entailment in material systems to the logical entailment of the model.

The modeling cycle in our scheme is linguistic, and so is tied to observer decisions as to meaning. The cycle of realization and self-assertion captures the dynamics that underlie the structure as it changes. Note the structure may change materially while maintaining its identity on the linguistic side. As we said above, the point of the whole enterprise is to relate the linguistic side to the dynamical side. Note that the two cycles are different at a fundamental level. The linguistics of the model, with its semiotic representation, are updated in a rate-independent fashion with discrete steps. Meanwhile the dynamical side is rate-dependent and continuous. For this reason, the two cycles cannot be linked directly without contradiction (Fig. 3). Pattee (1978) identifies the wave/particle duality in physics as such a situation. To deal with this dilemma, Pattee suggests that we deal with one account for the linguistics, and the other for dynamics, but keep the two sides separate. The connection between rules and the material context will therefore amount to a duality to the point of a complementarity. Thus, success in the application of our system does not lead to unity. The measure of success is when a complementarity imposes itself.

We can give an account of our scheme in a fashion that is less dependent on different levels, and it has utility. In Fig. 5, we show a different expression of Fig. 3. We express the linguistic modeling cycle as passing through the observed structure at level n, shown in Fig. 5 as the north pole of a sphere. Cycling at 90°, the realization and reinforcement cycle is an expression of dynamical change in the observed structure at level *n*. This cycle also passes over the north pole of the scheme. Note that the cycle that ties the linguistic and dynamical cycles together invokes complementarities as it binds the whole system at its equator. And all this is set in the context of laws, and the meta-observer who decides when the show is over. Any unified account is lacking, because it fails to capture the contradictions and complementarity. It is no accident that the literature of complexity has definitions of complexity that are at odds with each other. This lack of agreement as to the one definition of complexity has its roots in the infinities of Rosen's complexity forced into a smaller space by the modeling exercise. As the dynamics and semiotic linguistics clash, contradiction emerges.

5. From models to narratives

Let us now build on the implications of the Rosen modeling relation, captured in Fig. 4. In a metaphor, such as ''man is a wolf,'' characteristics of the wolf are mapped onto the man. Man is defined as the ''primary system,'' and the wolf as the ''secondary system'' (Hesse, 1980). In such a statement, wolf is not equivalent to man as in analogy. The wolf is a representation of the man. The one-way nature of metaphor is shown by the metaphor's inability to display anything new about the secondary system. A metaphor more clearly showing this unidirectionality is ''every morning is an open door.'' Compare the preceding metaphor with the unrevealing inverted statement, ''an open door is a morning.'' (Hesse, 1980). Metaphor arises in Rosen's modeling scheme as the model represents the material systems.

In Rosen's (1991) modeling relation, we see two patterns of mapping. One is the mapping whereby the model represents the material system. The model is thus a metaphor, and in this way works in only one direction. The model only models the material system, but the material system does not model the model. The second mapping in Rosen's scheme is the analogy between two material systems that both can be encoded and decoded into and out of the formal model (Fig. 4). In the analogy, both material systems are material analog models of each other. The analogy goes both ways. While the mapping to the formal model is a representation, the mapping between the two material systems is a compression down to only what is equivalent. An example of an analogic equivalence is the way that a paper dart and a DC 10 will both stall at speeds that are predicted by the formal model. Only the paper dart is made of paper, so being made of paper is dropped from the analogy. The two patterns of mapping are, respectively, representation and compression.

A narrative is not about the reality of a situation. Rather, the point of a story is to lay out in the open what the narrator suggests is important. Narratives are not about being objective, but are instead displays of subjectivity. Clearly in a narrative there is representation. There is also compression down to just what the narrator considers significant enough for it to be included in the story (Cronon, 1992). If modeling is representation, and analogy is compression, then a narrative is the outcome of the Rosen modeling relation. A narrative is the representation of a compression, which is integrated at a higher level of analysis (Fig. 6).

The beauty of a narrative is that it can rise above a model. While complexity is something that cannot be modeled, one can still tell a story about it directly. The ultimate device for addressing complexity is narrative. Allen et al. (2005) point out that science ultimately produces narratives. But it still uses models to improve the quality of a narrative. There is a timeline in a narrative as well as the time taken real-time in the process of telling the story. The narrative is at first one-dimensional. The consistency of models comes from their existence as points inside their parameter space, so models are zero-dimensional. Narratives in science are not about the truth, but they should be consistent with what is thought to pertain from observation. Improving the scientific narrative amounts to insisting that the one-dimensional narrative should pass through the zero-dimensional models. Indeed, this does improve scientific narratives. But thus improved, the narrative rises above the model. When the model fails or does not apply, because the story has moved on, the narrative is still in business. The narrative is an expression, not of the verity of anything, but of the values that are shifting as the story unfolds.

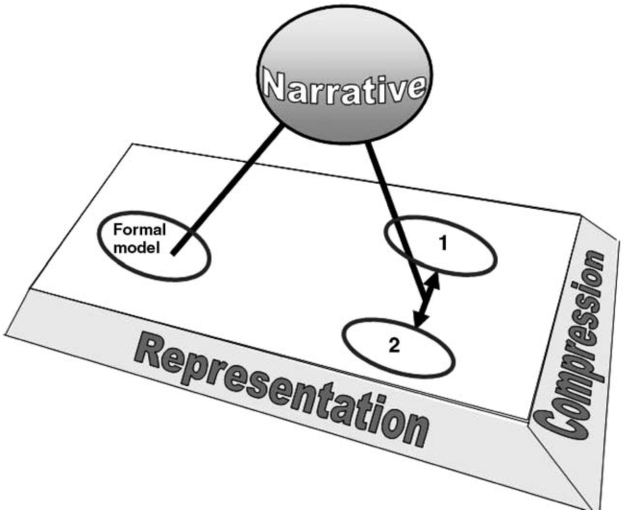

Fig. 6 – The Rosen modeling relation of Fig. 4 is now placed on the floor of a three-dimensional scheme. The narrative above is the *representation* of the *compression*. The narrative works at a higher level of analysis, and transcends the model. Narrative can still apply when the model is driven into contradiction, because it is about the decisions of the narrator, not some internally consistent representation as occurs in the model.

If the model representation in the Rosen modeling relation is fixed to a point in parameter its space, it tells something of the state of the system. Since the analogy associated with the compression goes both ways, there is something of a difference in the analogy, and this makes for something like a first derivative. From this, we can identify a phase diagram of state against velocity. If we plot a frictionless pendulum in a phase space, it follows a circular stable limit cycle. With friction the pendulum spins down to its resting point of a middle state and no velocity (Fig. 7). We can see the movement in the phase space as the narrative of the pendulum. State comes from the representation in the model, and the first derivative comes from the compression in the analogy of the Rosen modeling relation. With the simple attractor of the pendulum, it is a simple story that depends on the initial conditions of ''Once upon a time.''

Powerful narratives, like great pieces of music, feel as if they were inevitable when they are over, and we seem to agree on that. But note, even in a compelling story, the next line cannot be predicted. It is that feeling of inevitability that endows the great story with its ability to generate commensurate experience amongst independent listeners. The point of science is not prediction. Rather, the undeniable power of science comes from its capacity to get us convinced that we are all seeing the same thing, at least if we adherents to the same paradigm, the same story. Prediction makes the story convincing, which is important, but it is only one device for doing that. It is the convincing narrative that gets independent observers to agree that they are having an experience commensurate with that of other observers. Einstein was

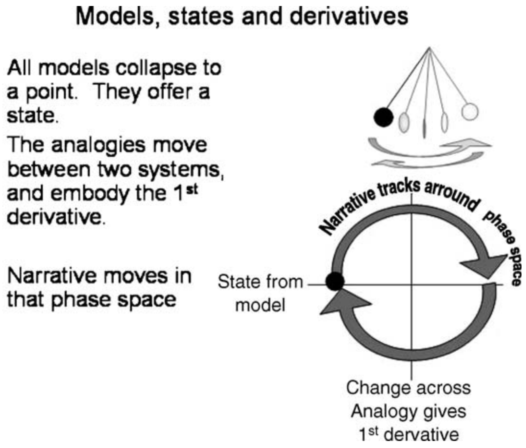

Fig. 7 – If the formal model gives an arbitrary fixed point, and the analogy indicates movement, then we can see the narrative as the movement of a point in a phase space. Here, is a simple attractor of the story of a pendulum. If the underlying model were chaotic, then the movement in the phase space of state, velocity and acceleration would never repeat. This full strange attractor would be the infinity that lies behind the local story told by the particular run of the equation.

surprised that our experience of the world should yield to mathematics. We are more surprised that independent human observers, including us, appear to agree that we are seeing the same thing.

In a constructivist world there is never a blank slate, and everything is always built on how past experience opened our minds. If all our independent experiences depend on our individual construction events, then it indeed is a puzzle that we can agree on much at all. The power of science comes from the capacity of its narratives to convince us that something is general, and we should agree on it. And this agreement arises even when the story is quite long and encompasses inconsistencies. Furthermore, we seem to be able to agree even when there is no logical necessity in the outcome. We agree on evolution and global warming, even when many of the detailed models are at odds with each other. Carbon dioxide has been a big player in past global warming events, and we know generally how that works. Increased temperature will increase evaporation, so as to make more clouds. The jury is still out as whether or not more clouds would sufficiently change the albedo of the planet, thus counteracting the warming. But even so, the story of anthropogenic global warming just feels right, and the science of it is confident. Working scientists generally agree that Kuhn (1962) was right about how science has an important social and political side to it. The review process is far from rational, and almost every scientist has been a victim of that at some time or another. Editors are politically influenced by their friends as to whether or not a new idea will be allowed into the literature. The intransigence in the early and mid-1960s of rank and file geologists in ignoring and resisting continental drift (as plate tectonics was then called) was impressive. Eric Schneider tells of the rough time an audience of oil geologists gave him on his early presentation as a graduate student. Only Turzo Wilson (the protagonist of the Hawaiian hotspot making the Pacific island chain) came up and assured the lad that he was right. So scientists now know Kuhn's grand narrative is worth believing. And yet historians of science nit pick Kuhn's narrative, to the point that there are two schools. The externalists agree with Kuhn, but the internalists say science is discovering things independent of the social setting. And the internalists do appear to be able to find Kuhn technically in error, even in the examples of paradigm shifts he chooses to discuss. One can be at odds with the logic of local models, but still have a story that is worth telling. Being right is not what it is cracked up to be. And it is narratives that rescue Kuhn from his inconsistencies.

In a pendulum there is a simple attractor and a straightforward story, but if we are modeling a chaotic system, then we get a strange attractor, which never settles down. In other words, the story of chaos never ends. In practice, the narrator does identify when they all lived happily ever after, but full strange attractors are infinitely dissectable, and they never end. The full attractor is not the whole story, and it cannot be because there is no compression as to what is significant. A given run of a chaotic equation is the narrative as told. If enough of the track is run, then the general form of the full strange attractor is apparent. It is that identification of the general form of the undefinable strange attractor that gives a powerful narrative its feeling of inevitability. We are in the end convinced by something of which we only get fleeting glimpses. In strange attractors, we need a third dimension to the phase space, the acceleration or second derivative. That indicates the force field, which, in the end, makes all the examples fit into an equivalent space. You never see the whole force field behind the narrative, but you still use it to get the feel for what is conceived to be happening.

There is a general issue here that harkens to some large scientific ideas, such as Heisenberg's uncertainty principle and Schrödinger's cat. We suspect that the huge influence of chaos theory on science and popular culture comes from a consonance with those ideas in physics. It appears to us that strange attractors are a special case of how we know things through narratives. And those huge ideas in physics resonate with how we know and come to believe things in general.

The unity in all this comes from narratives simultaneously addressing: changes of state, reversibility and irreversibility, symmetry and asymmetry, local focal and global tacit attention. Shortly before his passing, James Kay was working on an important issue, to wit there must be more to energy than the bookkeeping device. James asserted that energy is the capacity to change state, while work is an irreversible change of state driven by exergy (the capacity to do work) (Fraser and Kay, 2002). This allowed Kay to link thermodynamics and quantum mechanics, although the work was incomplete when we lost him. In narratives we see the local narratives tied to models. One can backtrack in a strange attractor by merely running the equation backwards. There is symmetry and internal consistency in this local part of the story. But as the narrator finishes dealing with one part of the story, the narrator and listener have been made open to appreciate some new part of the story. The narrator/listener has been constructed into something new and more open. This newly

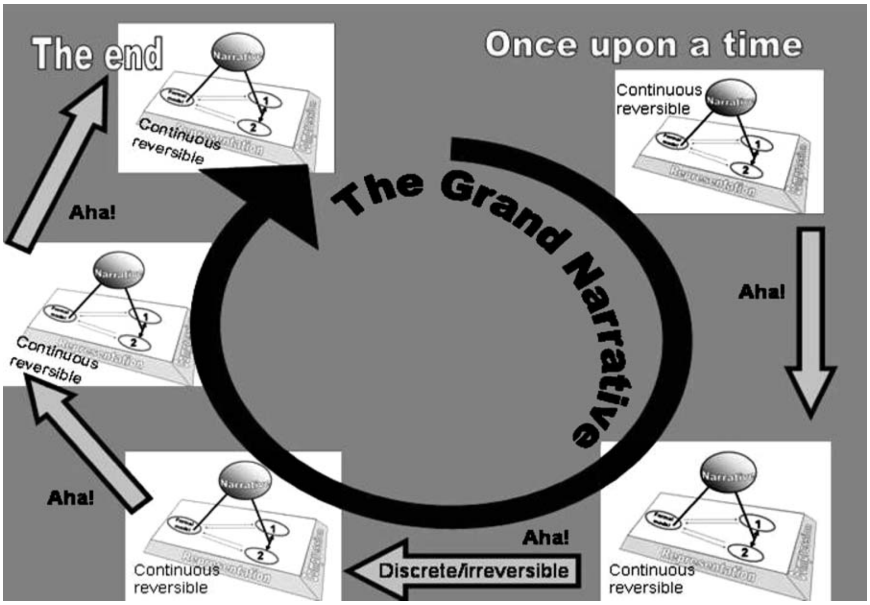

Fig. 8 – In a grand narrative, there are several different places in the story where unrelated models may be applied. Note that the application of the individual models is reversible and continuous. Just run the equation backwards. But as each model bolsters some part of the story, the narrator/listener is constructed in a discrete to be open to the next part of the story. The construction is by instantaneous "Aha!" moments, which moments are irreversible. Thus grand narratives (such as Kuhn's account of paradigm replacement) have two types of time frame. The local parts are internally consistent, while the whole may have tension and asymmetric development. The local parts of this figure are reproductions of Fig. 6.

constructed person can then appreciate some new part of the story based on a different local model. This process is asymmetrical. Once the narrator/listener has been constructed, the process is irreversible. Once you understand, you are changed forever. Telling stories is, in James Kay's sense, work. The goal directedness and the fulfilling of purpose in the whole enterprise lead to an asymmetry. Time on the attractors is continuous, whereas the "Aha!" of the process of construction is discrete (Fig. 8). In narratives there is a tension between Polanyi's notion of tacit versus focal attention (Needham, 1988). Thus, narratives do unite state with tensions across reversibility, symmetry and levels of attention. It is in this way that narratives remain robust, even in the face of inconsistency. The New Testament is a compelling narrative that embodies the Christian myth shared by many, and yet the Gospels as a collection have mutually exclusive, contradictory elements. The power of narratives, as with the power of myths, is their capacity to rise above contradiction, when the juxtaposition of large disparate issues is given meaning.

Allen et al. (2005) note that mimics lie to their predators. In this way, they tell a two-dimensional story, where one dimension is their evolutionary homology and the other is an analogy to the organism that is the mimicked model. As with so much in biology and social systems, in mimicry it is not the truth that matters, but rather the accommodation to what is thought to be true, even when the actor is misinformed. Self-knowledge comes from what the predator does; you do not know you are an item of prey until a predator treats you that way. In science the lie arises in experimentation, when the scientist says some version of, "No, really, it is that simple." So the narrative the scientist tells in experimentation is two-dimensional. The self-knowledge comes in the experimental results, when the world tells scientists that they can or cannot get away with their assumptions. The experimental results are a commentary on the two-dimensional lie, and so is itself a three-dimensional account that offers the scientist self-awareness. Narratives make us aware.

6. Application

McCormick et al. (2004) used the scheme outlined above to address the situation of salmon in the Columbia River. They identified that the logging, dams, agriculture and heavy harvesting have all broken the cycle on the side of the other. Sustainability is going to be a matter of repairing that cycle. On the side of the observer, they saw several models that were not so much competing, as complementary. Cycles of modeling for fisheries experts, Native Americans, toxicologists, ecologists and managers would clearly be different. We might expect the time zero, "Once upon a time" for each model to be different. The ecologist might wish to refer back to a situation before there were humans on the Columbia River. The Native American model would probably refer back to time before the Euro-American invasion. The toxicologist is more concerned with present influences that would shift some of the responsibility for system dysfunction onto players other than the chemical manufacturers. For the Native American model, a major problem is a spiritual matter of humans not offering proper respect for the world around them. For the fisheries scientist, the major concern is the harvest. The bounds of the

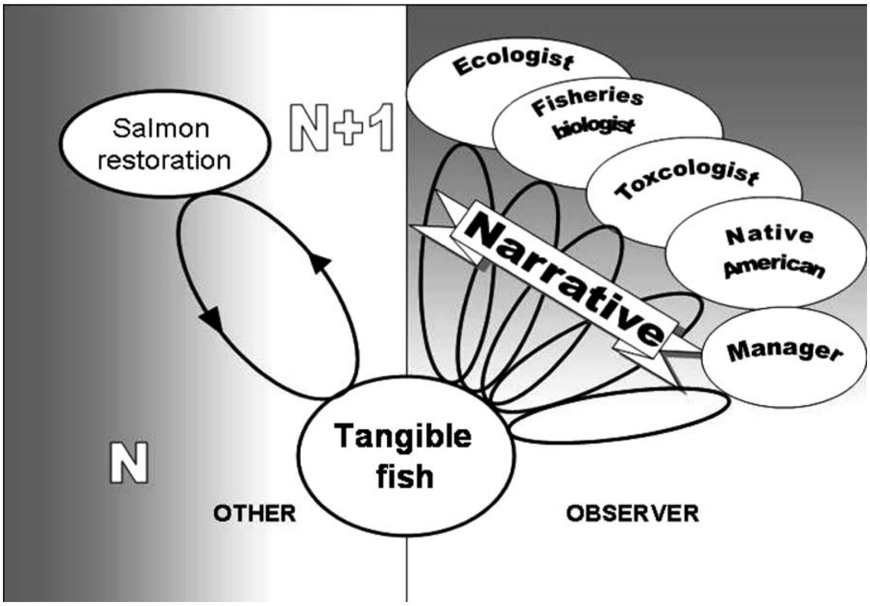

Fig. 9 – Application of the modeling cycles to create a narrative from the set of models regarding salmon in the Columbia River. The different articulations in each model are strung together in a larger narrative that juxtaposes the issues raised in the individual models (after McCormick et al., 2004).

fisheries model would nevertheless exclude harvest in the ocean, because we do not know much of where salmon go and what they do in the ocean.

Each one would offer a model, but the situation is complex because there is no way to calibrate all these valid postures so that they all fit into a meta-model. All these models can be calibrated, because they are models, and yet each is too local to address the critical issues of sustainability. The unification is achieved by letting each model contribute to a narrative (Fig. 9). Narratives can address complexity directly, because they do not pretend to be internally consistent. Narratives are going to be more useful if they are not false. However, narratives that are not false are not true either. The true, full chronology is never given account, and anyway would not be a narrative, because there would be no compression down to what is significant. The scientist pulling it all together raises the quality of scientific narratives by challenging them with calibrated models.

The utility of our scheme in issues of sustainability is the way it treats the ecological system as changing at its root. It captures both behavior of structures as well as changes in the structural nature of ecological configurations. There is never a time zero in biology, for there is always the history of biological change from before. The before might be prior to when the investigation started, or when the environmental insult occurred, or when the law was passed. Only a scheme that operates formally at structural and dynamical levels can do an adequate job. Sustainability invokes some long timeline, and that gives plenty of time for situations to be different at several levels. Also sustainability involves people and their values, so it is crucial to be explicit about meaning as well as dynamics. In matters of sustainability, one must always ask of what, for whom, for how long and at what cost (Allen et al., 2003b). Unfortunately, material nature does not offer benchmarks for sustainability independent of those criteria. We must decide for ourselves what are the answers to those human dilemmas, and take responsibility for those judgments.

As an example of how the narrative can be used, one can consider the success of the Whooping Crane Eastern Partnership (WCEP) in reintroducing the whooping crane, *Grus americana*, to the eastern United States (Glick, 2005). Reintroduction of cranes does not only involve hatching and releasing chicks, but also must include a context for their survival. In order to restore this context, conservationists needed to fix the cycle in the other that allows cranes to modify and realize their essence. Along with passing on DNA to their offspring, cranes must also pass along learned information that is not stored in their DNA. Most importantly for cranes, this learned information is their migration route and the avoidance of humans. Had WCEP just released captive-bred chicks to the wild, the attempt would have probably ended in failure. Instead, WCEP provided the chicks with the appropriate narrative for their survival. By dressing up like cranes, the technicians that raised the chicks were able to prevent human-imprinting on the chicks, and maintain their fear of humans. Distrust of humans is an essential ingredient, since the decline of this species is in part due to hunting. In addition, ultra-light planes were used to teach the chicks not just how to fly, but more importantly where to go during their winter migration.

Today, WCEP is able to release captive-bred chicks to the wild and these chicks are successfully taught by the adults in the population. It is much of the same information as would have been learned from their parents, before the decline of the species. Moreover, WCEP has begun to modify social and political aspects of this narrative by increasing public awareness through education. The success of reintroducing these cranes to their native habitat is a result of maintaining and redefining the same narrative that has been essential to this population for centuries.

7. Conclusion

At the outset of this paper, we promised to identify how the specialist view of the science of complexity is fundamentally at odds with the view of experts who think their system is complex in some informal way. We showed that the realist view of complexity lacks subtlety to a degree that will force simple solutions to complex problems, solutions that are wrong. If one takes our constructivist approach to complexity, then it becomes possible to manage the role of the scientists' perspectives and decisions. A realist definition of complexity is immediately in trouble, because one reality requires only one viewpoint. If complex systems are defined, as we and Rosen do, in terms of an incapacity to model them, it is possible to ride out emergence that is characteristic of complexity. One might even come to expect emergence, albeit unpredictable in its details. But we can only do this if we are in a position to recognize the role of the scientist's decisions. Managing for emergence involves changing a point of view. Managing for complex systems requires a meta-level of activity. We must consider the required changes in the managers' viewpoint, as human activity addresses the biogeophysical system.

In the body of the paper, we developed a protocol for dealing not only with changes in the material nature of the ecological system, but also the modeling side of the equation. In the end, we found that narrative is the favored device for addressing complexity. It is robust, even when models break down.

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