CRISIS SCIENCE FOR SUSTAINABILITY

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ABSTRACT

Sustainability science requires interdisciplinary and even trans-disciplinary frameworks for research in order to shift from disciplinary and sectorial studies to more appropriate ways of understanding whole system sustainability. While this shift is difficult to achieve within current traditions, an actual crisis seems to trigger many of the characteristics that would also be appropriate for holistic science. Disciplinary research tends to be the norm when we have a carefully planned research agenda and well-posed questions; but when we don't know the questions, as is the case in a crisis, we instinctively invoke trans-disciplinary modes of learning. We may thus learn a great deal about system sustainability and system research by looking at the characteristics of 'crisis science'. Here we review personal experience from scientific responses to oil spills in the 1970's.We suggest a general framework in terms of R-Theory (Kineman, 2012), which is a relational holon theory based on four archetypal domains corresponding to Aristotle's general explanatory hierarchy and many other similar frameworks that have been developed separately in various disciplines and perennial philosophy. We propose general development of "Crisis Science" as a complex systems research field that has strong parallels with holistic paradigms many are struggling to establish in ecology and environmental management. Not only is there a strong theoretical affinity between these two domains, but by promoting Crisis Science publically and in mainstream programs, funding may be more easily obtained for critical integrated research that supports both purposes. As part of a Crisis Science research program it is necessary to train between crisis responses, and shared principles and methods are possible across many holistic problems we face otherwise in anticipation of possible crises. Pursued together, Crisis Science and Holistic Science can establish the Anticipatory capacity we need to avoid crises.
Keywords: crisis science, oil spills, action research, system sustainability, complexity, holistic thought.

INTRODUCTION

A 2006 study of the state of interdisciplinary research in the health sciences, where the value of interdisciplinarity is perhaps most recognized, concluded that it was only weakly formulated and conducted on an ad hoc basis as the exception rather than the rule. The study identified levels of interdisciplinarity from weak collaboration to strong transdisciplinarity aimed *"toward a coherence, unity, and simplicity of knowledge involving an integral framework"*. Accordingly, they proposed an expanded definition (Aboelela *et al.* 2007):

> *"Interdisciplinary research is any study or group of studies undertaken by scholars from two or more distinct scientific disciplines. The research is based upon a conceptual model that links or integrates theoretical frameworks from those disciplines, uses study design and methodology that is not limited to any one field, and requires the use of perspectives and skills of the involved disciplines throughout multiple phases of the research process."*

Another review, conducted in 2010, ranked sustainability science among those fields requiring such transdisciplinarity, but concluded that there is wide disagreement on measures of interdisciplinarity with no foreseeable bridge between them *"barring a common agreement on a theory of knowledge creation"* (Wagner *et al.* 2011).

It is safe to say that there is no commonly accepted interdisciplinary or transdisciplinary framework and in the growing literature on studies of interdisciplinarity itself, this lack of ontological agreement has shifted attention to *interdisciplinary communication* as a surrogate, thus questioning if interdisciplinary science itself can be achieved and calling into question the standing Habermas-Klein thesis that disciplinary integration is possible at all (Holbrook 2012). Ironically, integral frameworks exist abundantly in each separate discipline, out of the evolved needs of these disciplines to address complex system problems, but they address interdisciplinarity for that discipline alone. We thus have a disciplinary approach to interdisciplinarity.

Sustainability science, although relatively new and debating a variety of frameworks (Palmer *et al.* 2005; Abraham 2006; Ostrom 2009; Kauffman 2009; Komiyama & Takeuchi 2011; Onuki & Mino 2011; Wiek *et al.* 2012; Vries 2013; De Las Heras 2014) is one of those fields in which the lack of interdisciplinary science is frequently lamented. Most of sustainability science involves sustainability of separate processes; and, even if it is interdisciplinary, it is nevertheless divided into sectors of society (such as agriculture, mining, pollution, etc.). An integral approach to sustainability of 'whole systems' is rare in the literature, given the lack of underlying definitions, lack of integral frameworks in science, and historical development of our scientific worldview. Development of 'system sustainability' has a long way to go; requiring both comprehensive discourse and whole system epistemology (Kineman & Poli 2014).

Most amazingly, as recently pointed out by the US National Science Foundation itself, sustainability scientists find it difficult to integrate even basic ideas of "stewardship" and "caretaking" into the dialogue, let alone the multitude of epistemological frameworks (Whyte, Ii & Johnson 2015). Nothing could be more important to system sustainability than to incorporate human protocols into our scientific frameworks, and nothing could be more central to system sustainability then concepts of human responsibility and stewardship. It is also the case, although we can touch it only briefly here, that indigenous and ancient science have a great deal to offer in restoring modern science from its current fragmentation, to a concept of the whole (Kineman 2005).

System sustainability is thus poorly developed for both technical and historical reasons. On the technical side, we are as far from understanding what defines a system and what makes it whole or sustainable as we are from understanding interdisciplinarity. The problem is enshrined in Western dualism, raising the question if current science is even capable of studying whole systems (including complex and living systems). Science as it has developed in the past three or more centuries appears to have been artificially constrained by mathematical assumptions and positivistic beliefs that allow consideration of nature only fractionally (Rosen 1990, 1999, 2003). These issues are central to the development of sustainability science from a system perspective.

In this paper we adopt the view that a unity of knowledge, along the lines envisioned traditionally in the system sciences, is possible (Rousseau 2014). Furthermore, we argue and present evidence that such modes of investigation are also quite natural and something we are instinctively capable of as cognitive Beings, especially during a crisis. We attempt to derive lessons for system sustainability and holistic science from field experiences on an oil spill response team, and we try to place this experience in the context of current literature on sustainability science needs.

The term "Crisis Science" came into use in the 1970's as part of a special research effort to study marine oil spills (Pollack & Stolzenbach 1978). Tanker and oil platform accidents were posing a significant threat to marine ecosystems, however prior to this time little was known about the behavior and effects of spilled oil. There was a sudden rise in concerns about coastal oil spills because, on the one hand national policy favored development of off-shore oil resources to gain independence from foreign oil imports, while on the other hand there was an equally powerful public lobby to prevent damage to the environment. The resulting clash between public policy and public values was met with allocation of new funding for a major interdisciplinary environmental assessment program to evaluate the risks of oil development. It was then decided to form a team of scientists as part of the larger assessment to investigate “spills of opportunity,” with the aim of finding out what happens to oil when spilled in the marine environment and what problems arise that would need action or would affect policy for oil development.

We review experience from that team – the “Spilled Oil Research (SOR) Team” – as an example of crisis science. Our aim is to examine the necessary conditions for emergence of interdisciplinary, collaborative, whole-system environmental and ecological research. Our thesis is that the automatic requirements of crisis science are the same qualities that we need to cultivate for long-term trans-disciplinary research and management of complex systems; that is, for development of sustainability science from a system perspective. The question at hand is if these lessons learned from crisis science can be translated from emergency situations to the kind of "creeping" environmental change (cf. Glantz 1999) we now face globally. This discussion can be framed most generally by examining the relation between four primary drivers of society: ethics, science, policy, and human activity (an initial four-quadrant whole-system framework).

Traditionally in the environmental sciences, research tends to be compartmentalized by institutional mission and discipline (Kobayashi *et al.* 2014). Both financial and philosophical criteria reinforce those divisions. Interdisciplinary collaboration thus tends to result from special funding and special needs, whereas its development more generally has been slow, even as human impact grew to affect entire ecosystems with tangible adverse affects on society. While the need for a more holistic approach is often recognized in the literature, neither science nor philosophy seem to have the necessary definitions for a serious study of whole systems. Roughly speaking, our dualistic worldview itself is what forces the development of integral frameworks back into disciplinary compartments. Even the most general view in physics explains almost nothing about the phenomenon of life itself (Schrödinger 1943; Kampis 1995; Rosen 1999).

The primary exceptions to compartmental and disciplinary research have been in times of environmental crisis or when a sufficient case could be made for anticipating a crisis, as for example in the creation of the Global Change Programs in the 1980's, and the Millennium Ecosystem Assessment in the 1990's. What is it about a crisis that engenders more holistic thinking and acting? If we can learn why that occurs, perhaps we can create the appropriate conditions for more routine support of whole-system science.

The SOR Team

Figure 1: Agency Cooperation for Spilled Oil Research

Here we examine experience from the USA's Spilled Oil Research (SOR) Team[1], and how oil spill crises established the conditions for interdisciplinary collaboration and whole-system environmental and ecological research. The initial collaboration was between the National Oceanic and Atmospheric Administration (NOAA) and the US Coast Guard (USCG) as indicated in **Figure 1**, but it quickly expanded to include other Federal agencies, such as the Environmental Protection Agency (EPA), State agencies, and municipalities as this small research team developed over the course of four years into national and international contingency planning. The SOR Team itself existed as such only briefly, between 1975 and 1979, but its great success stimulated development of permanent national emergency management agencies that exist today.

The SOR Team exemplified how science can become a critical factor in resolving conflicts between policy and ethics. When the supertanker Amoco Cadiz lost rudder control in a storm and struck a rock off the coast of France **(Figure 2)**, no one had an emergency plan for dealing with a marine oil spill of this magnitude, nor a sense of

Figure 2: Amoco Cadiz Oil Spill 16 March 1978 : Tanker grounding (left), one of hundreds of oiled bays (middle), oiled puffin from Les Sept Ills (right). (Photos: NOAA SOR Team and CNEXO)

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[1] Dr. Kineman served on the SOR Team from 1976 to 1979 and was one of the team's responders to the Amoco Cadiz spill.

priorities for protection. Knowledge became the first priority in a situation where we hardly knew what questions to ask, let alone how to answer them.

The US SOR team responded immediately, with permission from the French government, to study the spill for research purposes; but it quickly became a science advisory team helping with critical decisions. The team had been gaining knowledge from previous spills, but each incident posed new problems and new behaviors. Some known behaviors could be studied by deploying pre-planned experiments, such as trajectory tracking and prediction, chemical weathering and dispersion, and assessment of vulnerability of coastal resources based on geomorphology and biotic factors; but the team had no organized approach to studying the biological impacts and very limited studies of cleanup methods. There were few in-depth studies of previous spills to draw on, and thus thousands of unknowns loomed.

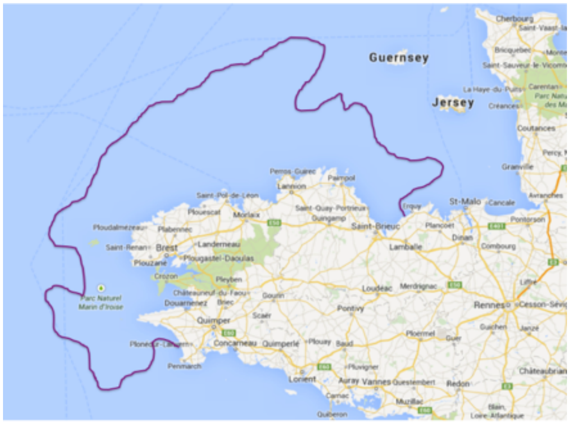

Figure 2: Red line shows extent of observed oil from Amoco Cadiz Spill
(Map data ©2014 Google; extent from Maurin, 1984)

Figure 3 shows the extent of floating and entrained oil that was released from the tanker as France's West and North Brittany coastline became acutely impacted for 350 km (Maurin 1984). The ship broke in half and the compartments ruptured one by one as the oil drained from each, creating a 'domino' effect. Over the course of a week the entire cargo of 1.6 million barrels of oil was released into the sea, of which one third came ashore oiling hundreds of bays (**Figure 4**) on the Brittany Coast (Hess 1978).

What could be learned quickly became critical in advising policy and decision-makers, especially to balance difficult practical and financial choices with societal values and environmental ethics. Decisions had to be made about where to place the strongest defenses against arriving oil, how to treat oiled sea birds and mammals, what to do with oiled kelp forests, sea grasses, mud flats and lobster bins, how to clean, or if to clean, oiled rocks, marshes and beaches, what crops should be destroyed due to contamination by toxic fumes, how to select safe disposal and recycling sites, and onward into a nightmare of often conflicting criteria and priorities.

Figure 3: Oiled Bay (Photo: Jean-Pierre Prevel / AFP)

One immediate question was when to use dispersants that dissolve the oil into the water. If they are used too close to shore, the effects of the oil are severely worsened for intertidal and pelagic life. Neither France nor the USA had a policy on the use of dispersants, although evidence was building that a limit on their use should be set at perhaps 25-50km from shore. The Amoco Cadiz was aground only three kilometers from shore, and the visual impact of the oil was severe. Consequently, various industries, in addition to the oil companies, exerted political and economic pressure to remove the oil from sight quickly, to minimize the impact on trade, tourism, and public perception of the parties involved. The need for scientific knowledge was thus driven by these choices between what might be best for nature and what might be best for various human interests, some laudable some not. There were, for example, efforts to clean oiled rocky shores by pressure-washing the rocks. Only later, when the science was clearer, was it realized that pressure washing (**Figure 5**) did more harm to attached organisms than leaving the oil in place and allowing a more long-term natural recovery. After years of oil spill responses, experts generally concluded that many cleanup efforts were futile or even harmful, except where oil could be removed in bulk without doing further damage.

Figure 4: Pressure-washing a rocky beach
(Photo: Jean-Pierre Prevel / AFP)

Citizen work forces formed quickly and were critical to the cleanup effort. Professional and volunteer crews were organized for beach cleaning using raincoats and breathing masks for protection (**Figure 6**), and shovels and buckets to remove oil in quantity into large pits dug for transfer to tanker trucks. Transportation networks were established for moving collected oil to recovery sites. Despite a strong and resilient population, the impact on the physical and psychological health of individuals, families, communities, and the nation was also an important concern. The team itself had recently added a social scientist and psychologist to the existing complement of physical, chemical, and biological scientists.

Figure 5: Hand collection of oil
(Photo: Jean-Pierre Prevel / AFP)

The spill created the largest biological kill of any spill to that date, littering beaches with millions of dead organisms that washed ashore weeks after the spill (**Figure 7**). The entire local population of puffins on Les Sept Iles, re-established after the Torrey Canyon spill off England, was again destroyed. Toxic and pathogenic petroleum compounds accumulate in biological tissues and become concentrated in the food chain; but avenues for toxic chemicals to enter the food chain were a major unknown.

The team learned in previous spills that different parts of the oil can separate and take different pathways, part floating in emulsified masses, other parts dissolving in the water, and heavier components sinking or attaching to sediments. Oil that finds its way into low-energy environments will degrade more slowly and possibly be re-suspended in the future. Ultimately oil is biodegradable, but intermediate products in the degradation process can be more toxic than the original oil. What is in one sense a natural organic compound becomes a serious pollutant in the wrong quantities, in the wrong place, and at the wrong time. In a high-energy environment, recovery may take 10-15 years; in low-energy environments, much longer. And there are permanent changes.

Figure 6: Massive kill of Urchins and other life at Amoco Cadiz oil spill (Hess, 1978)

Fresh oil from the spill is very toxic and affects some organisms immediately and severely. It is thus hard to study the acute phase biological impacts unless there are prior studies to establish a baseline of what existed before (Kineman, Elmgren & Hansson 1980; Glémarec & Hussenot 1982). Other kinds of organisms are robust enough to survive, and their tissue burdens of ingested oil are good indicators of levels of impact. Mortality rates of various species also indicate levels of impact. Still, generally useful biological indicators to assess ecosystem health and recovery have been difficult to develop. Research continues on the fate and effects of oil on biological resources and human populations.

Lessons in Sustainability

Aside from learning about oil spills, the SOR team introduced an entirely new mind-set about emergency response and preparedness. One result was the organization of contingency planning around the country, which led to formation of permanent disaster response agencies; and now, decades later, the US Department of the Interior has re-invented the concept of the crisis science team for response to all kinds of emergencies for the purpose of doing both emergency and long-term interdisciplinary science (Salazar 2012; Lollo 2013). In other words, we have now recognized the concept that a very different kind of science takes place during crises that is critical to problem solving in general. Though we learned this lesson from the immediate needs of a crisis situation, it nevertheless applies as a much more fundamental need, which is the need for *anticipatory science*. The message from Crisis Science is clear: *science is a critical factor for uniting policy and values to guide action in a complex situation.*

The principles of Crisis Science may therefore apply to other complex environmental and ecological problems that are perhaps more gradual crises resulting from human dominance of the Earth's systems and corresponding feedbacks; as through climate change, changes in the patterns of severe storms, biodiversity loss, land and water use conversion, disease vectoring, nitrogen loading, and much more including, perhaps, sudden events from system instabilities that we do not yet know of. "Creeping environmental change" (Glantz 1999), is less obvious than an ugly oil spill and doesn't automatically trigger an emergency response, but it is perhaps more dangerous and just as complex. Without the urgency of a crisis we are slower to react and less likely to be triggered into interdisciplinary whole-system thinking. We still think we know the important questions or have time to answer them, when we may not. Ecosystem complexity means that we will be surprised. Rather than thinking that we can respond traditionally, from the 'bottom-up' (i.e., from well-defined disciplines to whole-system synthesis), in ways we have prepared for; we need to think instead that we will respond first from the 'top-down' (i.e., from whole-system inquiry to new interdisciplinary requirements), in ways we cannot know in advance but must nevertheless discover.

This reasoning leads to a very important consideration about science. To prepare for the unknown, we need a more whole science than has yet to be articulated. Synthesis of assessment components is a completely different thing and may not reach the same end; it is assembling parts in a prescribed manner, knowing in advance what questions are important and what parts will be involved in the result. Complex systems research, on the other hand, requires a concept of the whole to identify where we place value, how system components relate to each other, and what requires study or action. Others have noted that a typical complex system study will often expand *"from a particular issue or resource to a broad set of issues related to ecosystem processes across scales and from individual actors, to group[s] of actors to multiple-actor processes"* (Olsson, Folke & Berkes 2004). As such, the present discussion of coupled human and natural system models (e.g.: Berkes, Colding & Folke 2002; Anderies *et al.* 2006; Fischer-Kowalski & Haberl 2007) may be too limited if we do not move from 'coupled' to 'integrative' frameworks in which more general principles of organization can be considered.

The SOR Team's basic assumption has been reconfirmed in more recent coupled system studies – that *"research on coupled systems must include not only separate site-specific studies but also coordinated, long-term comparative projects across multiple sites to capture a full spectrum of variations" and that "it is critical to move beyond the existing approaches for studying coupled systems, to develop more comprehensive portfolios, and to build an international network for interdisciplinary research spanning local, regional, national, and global levels"* (Liu *et al.* 2007). Such a network was in fact built for national and international oil spill contingency planning, as a direct outcome of the SOR Team activity.

However, by framing research in terms of "coupled systems" we preserve a possibly limited idea that human and natural systems, or social and ecological systems, must be studied separately, or more extremely that they obey fundamentally different laws. The meaning of such separation is that we can be concerned with their interactions, but not with deeper commonalities. Many questions may be unanswerable in such a limited framework. Instead, we need to develop the ability to look at a system and analyze it in terms of its composite and sub-system wholes, not only its fractional and separated parts. In other words, a truly integral method would allow us to decompose and construct (analytically or actually) whole systems in terms of whole systems. When we can see, for example, that pollution involves whole enterprises that produce the pollutant, whole biological systems that degrade it, and whole societies that clean it up, we can begin to ask the right questions of each sub-system; that is, the questions that will lead to effective policy or management actions at multiple causal levels. The field of medicine provides an appropriate comparison, in which a whole system can be kept whole (i.e., alive) only by retaining and sometimes even replacing its whole components. As a minimum, we know that solutions need to be integrated with the whole system if they are going to work without disastrous side effects. The emerging field of "eco-health" is taking such a medical and physiological perspective (Pimentel, Westra & Noss 2000; Waltner-Toews 2004; Rapport & Maffi 2011).

Whole-system research and management is normally discouraged, even disparaged, outside of crisis response because of two critical factors. First, we do not have a suitable epistemology for doing whole science, despite many efforts to reach in that direction (Patten & Odum 1981; Marshall 2002; Walker *et al.* 2004; Cornish-Bowden & Cárdenas 2005; Clark 2007; Jørgensen *et al.* 2007; United Nations University 2011; Kasser 2013; Gunderson 2013; Patten 2014; Allen *et al.* 2014). The reason for this lack, in the face of valiant efforts, may be deeply rooted in taboos against holistic research and tenacious preservation of current modes of thought (Murray 2005). Secondly, our institutions are too fragmented to operate more holistically even if we did have a more integral science. In crises, however, these barriers tend to be set aside. We then have the excuse to behave differently and, it seems, more appropriately if the right planning is provided. Surprisingly, studies show that people generally behave more reasonably rather than less reasonably during a crisis if they are honestly informed and allowed to use their natural abilities (Mileti & Peek 2000). The question, then, is if this ability can be enhanced with better preparation.

Institutions, on the other hand, may not act reasonably if they have not anticipated the problem, because most institutions cannot suddenly become anticipatory learning organizations, which people are by design. Institutions therefore need to build anticipatory components in advance in order to produce the information, methods, and options that may be needed in a crisis, or that may avert the crisis. The problem with waiting for a crisis before engaging whole thinking is that the situation may then overwhelm us. We may indeed react reasonably but the crisis may not grant the necessary time. We need to learn how to anticipate.

Perhaps science itself suffers from something like Garrett Hardin's "tragedy of the commons" (Hardin 1968) in that individual gains of disciplinary science are compartmentalized just like the individual use of common land that Hardin described. When separate interests maximize their efficiency they collectively lose sight of the whole. When a crisis threatens the entire system, we become whole-system thinkers, but only out of short-term self-interest to re-establish our individual benefits; to "get back to business". While Hardin, 30 years after his classic paper on the subject, admitted there may be other complex feedbacks that could prevent the inevitable loss of the 'commons' that he predicted earlier, he still insisted that the solution cannot be scientific or technical, only moral (Hardin 1998). He may be right that the solution cannot be technical, but perhaps it is possible to make science more moral, more values-relevant, by expanding it to modes capable of studying the principles of whole systems.

Both policy and values are system-level characterizations. The message of crisis science, then, is that science must also have whole aspects to reach the same level where systemic problems can be solved. Can scientific knowledge make the leap to scientific wisdom, where it is then relevant to society? It should at least be conceivable, and we will argue that it is necessary if science is to serve its function in society. We can thus extract a number of lessons from crises that apply equally to all complex system research and management. Furthermore, we may be able to extract a general theory that will help us integrate societal leadership domains consisting of ethics/values, science/technology, policy/culture, and business/activity.

Conflict Resolution

The SOR team existed under unusual conditions. It was created to gain knowledge to help resolve the expected impasse between development policy and environmental values. But that fundamental need for scientific information to drive decisions also existed on scene during the crisis, a fact the team had not initially prepared for. At both levels the organizing principle was a need for conflict resolution.

As another example, it took many decades for climate change science to achieve the level of effective social engagement necessary to arbitrate policy and ethics choices. Science is aimed at developing capacity through knowledge and technology. The need for such capacity is clear during a crisis, but at other times special interests tend to force compartmentalization and thus obscure the role of science in resolving conflicts. Contrary to the argument that science should be 'pure' and policy/ethics neutral, only when science has expanded to address whole-system issues can it then avoid being marginalized and thus fulfill its natural role in resolving conflicts that exist at the level of whole systems.

The three leadership quadrants in **Figure 8** – ethics, science, and policy – is a well-known framework for considering complex socio-environmental problems and it often appears in educational structures (Shrader-Frechette 2012).

The same principle that drove the need for crisis science, that it can resolve conflicts between policy and ethics, may be equally true for each of these domains; that good policy can resolve conflicts between science and ethics, and that good ethics can resolve conflict between science and policy.

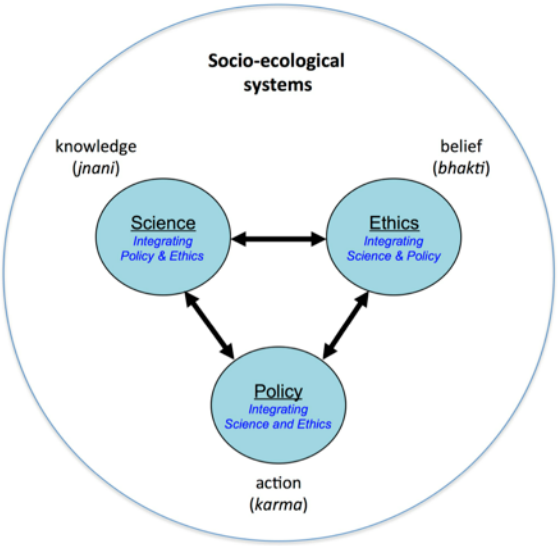

Figure 8: Socio-Ecological Leadership

This fundamental three-way relation between leadership domains (and the systems they affect, which are the fourth quadrant) has very deep cultural and historical roots – in Greek philosophy in terms of Aristotle's hierarchy of natural explanation or 'causalities' consisting of *final, formal, efficient, and material* aspects of nature (Kineman 2003; Falcon 2012), and much earlier in Eastern philosophy in terms of Vedic non-duality (Kineman & Kumar 2007; Katz 2007). In Vedic philosophy the four quadrants are known as the "four faces (or feet) of Brahman", in Sanskrit described as *bhakti* (belief/devotion), *Jnana* (knowledge/wisdom), and *karma* (action/destiny), each and together guiding what actually happens in the world, *satva* (material existence/events, the fourth quadrant). These general categories also correspond with social classes that appear in nearly every civilization as *priests, leaders, managers, and workers*. In Vedic philosophy, smooth running of society was thought of as a proper balance of these four quadrants, which were also represented 4,800 years ago in pre-Vedic (Harappan) archaeology (Kenoyer 1998). However, that balance seems very hard to achieve today, unless exceptional circumstances or personal practice allow it. And yet one might well say that the most "usable science" (cf. Dilling & Lemos 2011) during a crisis, and perhaps during any complex or uncertain situation, involves such a unity of systemic causes.

Aside from its appearance in perennial philosophy, archetypically similar four-quadrant schemas have emerged heuristically and empirically in many disciplines, although at present we can only speculate about their generality. These frameworks tend to exist in disciplinary isolation, but they may indeed reveal a common pattern in which the four levels can be seen as a repeating cycle of causal categories (Kineman 2011). The cycle may be generalized to terms such as *'values'*, *'knowledge'*, *'actions'*, and *'events'* (that the first three govern); or other similar patterns of causation, taking the four quadrants as an hierarchical cycle of archetypal causes (Louie & Poli 2011; Kineman 2011). The approach has received fledgling attention as 'holon theory' (Koestler 1970; Checkland 1988; Edwards 2005; Kineman 2012).

In social science a very similar framework for understanding systems is represented in the practice of "Participatory Action Research" (PAR), defined on a general cycle of *'reflecting', 'planning'*, *'acting',* and *'observing'*, as shown in **Figure 9** (Foshay 1998; Coghlan 2011; Sankaran & Dick 2014; Sankaran *et al.* 2015).

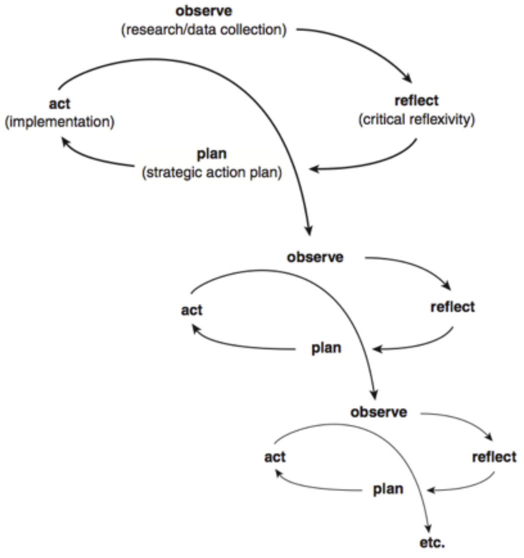

Figure 9: PAR Cycles (Koshy 2005)

In the management domain, Peter Senge's "Fifth Discipline", or "Learning Organization" (Senge 2006) is based on a similar cycle; as is, more loosely, Snowden's Cynefin (Snowden 2000). There is an implicit fifth level of all such cycles, which is the organizational schema itself – how natural causes are related to each other in a creating and learning cycle. A study of cultural cosmologies claims that indigenous creation beliefs collectively fall into the same four causal quadrants (Wilber 2007). In environmental assessment fields a similar cycle appears in the *"driver, pressure, state, impact, response"* (DPSIR) framework, officially adopted by the European Union (Kristensen 2004). In DPSIR, 'response' can be seen as a fifth level unity or a repeat four-quadrant DPSI cycle, suggesting a self-similar holarchy of natural causes, as implied across disciplines and from ancient times.

The difficulty proposing such cycles as a general schema, is that dualistic science beginning at least with Aristotle, viewed these levels of causation or explanation as an absolute hierarchy from God to material existence (in keeping with Abrahamic theology which views creation as a hierarchy from Heaven to Earth); and once a cycle of causes is represented as a hierarchy of causes, a line can be drawn to distinguish creation from natural law, religion from science, and so on. Prior to such dualism, however, Eastern philosophy presented a clear four-quadrant cyclical causality in which origins are part of nature. For example the Chandogya Upanishad identifies four quadrants of a creative and active cycle, with self-similar (holarchical) levels. The most general quadrants were given the Sanskrit labels: *ayatanavat*, meaning 'hearing' or 'having a home' as a possible metaphor for contextual origins and values (Aristotle's 'final' cause), *jiotishmat*, meaning 'sight' or 'vision' as a possible metaphor for formal constraints and knowledge (Aristotle's 'formal' cause), *prakasavat*, meaning 'breath' as a possible metaphor for change and manifestation (Aristotle's 'efficient' cause), and *anantavt*, meaning 'speech' or 'expression' as a possible metaphor for actual existence and results of change (Aristotle's material cause) (Muller 1876; Chatterji 2007). In current natural science, however, the 'higher' systemic or contextual causes are usually summarized heuristically and reified as probability, quantum vacuum, space-time geometry, universal constants, dark energy, re-emerging concepts of ether, etc. Clearly these philosophical speculations require much greater development that is beyond the present scope of this paper except to mention that a general understanding of systemic causation may indeed be possible based on an integration of both ancient and current thinking.

By the same reasoning we could say that the kind of science that is least usable for complex problem-solving is dualistic, highly fragmented, disciplinary science that avoids relations with policy and ethical dimensions. To be clear, that includes the mechanistic worldview that most of science is based on. There is no suggestion, however, of eliminating disciplinary science, mechanistic science, or compartmentalization. The separation of disciplines and domains has its purpose and societal function; and mechanistic reduction is a necessity even of something as basic as measurement (Rosen 1978, 2003; Morley & Renfrew 2010). However, these considerations suggest that another layer should be explicitly developed in each field, one that transcends the conceptual boundaries of the machine metaphor by design. In particular, it must involve an explanatory framework that identifies the components of whole systems at the level of all four of the domains in **Figures 8 and 9**, two of which are physical and two of which are contextual (i.e., have effect via information relations). Without such a holistic framework to integrate human and natural contexts with physical phenomena, solutions remain partial. The same conclusion is emphasized in recent advocacy of "solutions-oriented science", in particular that we must increase our understanding of the contextual dimensions of complex systems, those involving values and decision-making. Unfortunately, we have yet to define a truly holistic framework that can get us beyond the rhetoric, to actually integrate the constructivism of solution orientation with the reductionism of problem orientation (Palmer *et al.* 2004a; b; Kasser 2013; Miller *et al.* 2013b).

Preparation

The greater philosophical view discussed above was not part of the team's thinking at the time, nor later for most. Members of the SOR team were a rowdy bunch, not much concerned with transcendental thinking. The team was immensely practical and often the most engaged group on (and off) scene. Team members risked danger on many occasions, for example flying their own scientific reconnaissance missions into remote areas and even war zones. Nevertheless, philosophy was evident at the level of team psychology, and also in behind-the-scenes guidance and planning, following a wise and radically new concept that in essence was 'participatory science'[2]. The team was asking: *"What can we learn by participating in a crisis response, as it unfolds?"* There are other parallels for participatory science in behavioral science (e.g., LSB Leakey's famous revolution in great ape research, new paradigms in management, and many more domains in addition to development of PAR).

The SOR team prepared itself as much as possible through training exercises, using what was known about oil spills. That in itself was a rapidly changing paradigm as new facts were accumulated. But perhaps equally, the team prepared itself for complexity. That was a psychological preparation, a new way of thinking about problems in an integrative way. Every problem held a lesson to be learned, and the team was there to learn it. Their initial surprise was the extreme demand for that information. Normally, general science (perhaps aside from competitive technology research) is 'pushed' by its practitioners not 'pulled' by its users. The crisis makes this point: A decision must be made with the best information or experience available at the time.

By analogy one would also expect to develop integral and holistic methods of research to prepare for more gradual change and long-term research on complex local to global problems, including climate change, species extinction, energy resources, natural hazards, economic systems, water use, land use conversion, agriculture, etc. As the spill team learned, disciplinary training does not necessarily translate into an operational capacity to deal with emergencies. While each member of the team may have begun as a disciplinary specialist, each became a 'rigorous generalist' with a number of specialties, trained to expect the unexpected and often to substitute where needed. If an ethic emerged, it was readiness and service.

Discovery

Crisis science is initially about discovering the questions that need to be answered. In disciplinary science we can become complacent about this initial process of open and creative inquiry, which often involves pure intuition. It is the hidden process that rarely gets published. Disciplinary science tends toward identifying the main questions in prior work and answering them, or improving the answers in current research. Most work thus assumes an incremental development with cautious progression from question to answer to next question. Most applied research and increasingly popular 'policy-driven' research, may expect to be given questions up front; by managers, engineers, policy leaders, decision makers, or society without taking full account of formative contexts; whereas in unfamiliar territory, the questions themselves have to be discovered (Ackoff 1962).

Unfortunately, where fields of science exist that place a heavy emphasis on discovery and exploration of new and perhaps unexplained phenomena, those fields tend to be marginalized. Crisis science violates many norms of methodical research and standard controls; and yet it gets immediately to the point of recognizing uncertainties in

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[2] Mention must be made here of the visionary role of John Robinson and operational leadership of David Kennedy; each critical to the SOR team's existence.

subject and method. It is kept honest by the situation, which is so well scrutinized that fantasies are quickly removed. The counter argument in favor of disciplinary science might be that it is better governed by methodical and rigorous inquiry, building on previous discovery, being under less pressure for immediate results.

But the crisis approach is less reducible overall, even though it relies on the best of our present knowledge and ability; the tried and true models that work. By becoming an introspective part of a complex situation, it produces information about complexity that is immediately relevant and otherwise unavailable. While being highly practical, it does not exclude the wild notions, which often lead to some of the most important discoveries in real time. Its methodology is thus neither incremental nor random; it exists at the beginnings of an ordered process and largely establishes its own order. Perhaps its key feature is that it evokes the cooperative spirit and creative problem-solving abilities from those willing to dive in head, heart, or feet first. It instantly pulls together the natural human intuitive and synthetic capacity, if we train ourselves to allow that. In considering a whole system, one is unavoidably challenged to tap whole personal qualities within, and generally participants find that highly rewarding, even addictive.

Surprise and Reorganization

In the case of environmental crises it is obvious that the system is capable of unexpected behaviors, even extreme surprises, so knowledge is combined quickly. In a crisis we are forced into complexity. Having no way to predict the future in a crisis we instinctively monitor a wide range of processes to see how they are interacting. But we are often caught off guard because our normal thinking, which is fragmented into partial views, may not have provided adequate experience for what is encountered. Each separate dynamic can be projected to a logical conclusion that certainly won't happen in that specific way because of the influence of many other factors we don't know, acting together. The higher-level contextual influences that constrain or 'attract' the system to a certain condition are very difficult to discover in precise terms but they can be anticipated through intuition. We assume such knowledge is based on prior experience, but it is revealed to us in subtle and not entirely certain forms. Decisions have to be made under uncertainty (Devanney III 1971).

It is impossible to apply disciplinary methods without some prior experience of the given situation, or first discovering which processes might be important. Therefore, we must look for emergent behaviors, and perhaps even test responses to various treatments; because we do not know from where the impacts will arrive, or how effects will be distributed. We become true explorers, which is a mode of science that is normally quite restricted and for which we have spent very little effort developing methods.

It seems that we study complex systems primarily when there is a crisis that forces it on us, and otherwise we study nature's more predictable behaviors that can be compartmentalized and organized into disciplines and separate process models. The presumption that compartmentalized research can later be synthesized into information and methods for predicting complex behaviors may be false (Louie & Poli 2011): such predictions have often failed in complex situations, except to predict a range of possible behaviors. The issue is simply that summing up the separate processes does not get us to the overall behavior of a complex system, so we have to look from the 'top-down' (from system to phenomenon) as well. But perhaps even so there are natural precedents in system design that we can learn from.

The mathematical biologist Robert Rosen wrote that a complex system is one that can be interacted with in many ways (Rosen 1991). A machine, then, is the opposite: we have designed it to work according to one model that prolongs a desired behavior despite future conditions. If a part breaks or conditions change too much, the system stops working. Organisms are not machines, but they also realize a model; one that has evolved with the system as a prediction of expected conditions. Thus organisms can modify their behavior in anticipation of the future to survive as a species rather than an individual system (Rosen 1985). But when a component of an ecosystem fails, or even many of them, the system does not stop functioning, nor does it evolve its own model, it reorganizes as an ongoing system. Ecosystems, by combining the adaptive behaviors of organismic components, can re-design and change into something that works differently (Gunderson & Holling 2002). While we can thus say that an ecosystem will probably 'survive' most changes, it does so by becoming a different system; it may no longer provide the goods and services we want or had before.

Generally, dramatic re-organization of an ecosystem is associated with catastrophic shifts between different kinds of systems, turning over species and functions (Scheffer & Carpenter 2003). If ecosystems have developed over a long time, catastrophic re-organization can revert them to an earlier stage or an entirely different regime. Both crises and more gradual reorganizations involve the failure of natural organismic models to anticipate future conditions. It is not surprising, then, that our own ability to predict future reorganization of an ecosystem would also be limited. If there is another higher level of understanding by which we may be aware of and bring about future possibilities under a variety of scenarios, we are then involved in *"Anticipatory Science"* (Miller, Poli & Rossel 2013a), which itself has natural precedents in, for example, cultural evolution (Banathy 1996, 2010) and niche-defining phenotypes (Day, Laland & Odling-Smee 2003; Odling-Smee, Laland & Feldman 2003; Kylafis & Loreau 2011).

Anticipation and Societal Decision Making

Crisis science was born from anticipation of social conflicts from oil development. It was first imagined to have the specific objective of learning the behavior of spilled oil, since this knowledge could not be gained from laboratory or field experiments. Immediately, however, it was discovered that the approach itself had to be *anticipatory*. That is, it had to deal with complex, uncertain, or unknown processes and foresee multiple possible outcomes. Some of the best tools for doing that may come from thinking in terms of analogy (Glantz 1988). We thus learned something very important about both crises and complex systems; that interacting with them necessarily involves anticipation; a capacity we have as instinctive behavior, but one that is not well understood by science.

The time between crises might be described as a period during which we have switched off our anticipatory capacity, or perhaps have come to anticipate the status quo. Once surprised, we should then be alert to new possibilities and new modes of science that are suited for studying complex systems, but it is much safer ground to predict specific results of known mechanisms. Scientists are legitimately concerned about being held accountable for personal failure (Glantz 2001), but then help establish the greater failure of science itself by focusing too narrowly.

Into this void – the lack of real complexity science – come architects of 'policy analysis' (Pielke 2007; Patt 2008), which is claimed to be a higher level integration of science for decision-making within value-based scenarios, evaluated by "honest" experts in evaluation itself. However, we need to examine possible flaws in this thinking. First, these recommendations themselves say they must be based on the "best available science", which is arguably best integrated by scientists. Second, the methods that will be applied by policy analysts, once freed from the rigors of normal science, may not involve testable approaches that are recognizably analytic or synthetic. The primary method for policy analysis is constructive sense-making and its aim is to outline and perhaps expand policy options; but it often slights the role of objective science claiming that science is incapable of commenting fairly on what is 'best' generally or even specifically (Sarewitz 2000). Paradoxically, policy analysis claims to use 'scientific' building blocks – essentially facts that can be re-organized into a story – but it tends to deny that there is any 'right' story; each having its own bias that at most one can reveal 'honestly'. Supposed facts are thus boundary conditions on human constructivism; they do not 'add up' to anything themselves suggestive of policy or ethics. But these assumptions should be seriously challenged. Science could speak for itself if it could bridge the gap to complex living systems; to consider ethical and political aspects of various socio-ecological scenarios (Glaser *et al.* 2012).

During a crisis there are many individual and social constructions that take place. They represent a cultural instinct that is useful if the situation is not too unfamiliar to us. But to rely on a socially constructed process of decision-making by itself, in a crisis or even under more gradual complex change, without the addition of scientific responsibility to facts, could easily lead to a meaningless response. In other words, a wrong solution may seem attractive at the time on purely constructivist grounds, but our experience-based sense of what is good may not hold up to a more thorough system analysis in which we study precedents in nature. This is because we have limited experience of crises. We avoid it for obvious reasons. Decisions under uncertainty can be made by analogy to prior experience (Glantz 1996), and intuition may be the biological equivalent to deciding by analogy, but one must methodically build that experience base, and if not on an individual basis, then by collective scientific methodology.

However, in favor of dialectical constructions we can say that enough facts to comprehend a complex or crisis situation are perhaps never available, so one is forced to balance factual knowledge with instinctual or practiced responses, and finally to fill in unknown territory with intuition. We are humans and one good point made by policy analysis is that it is inherently a human endeavor tapping natural capacities. But even so, there is no reason that science cannot expand to include the study of analogical and anticipatory phenomena and methods, nor why policy analysts within the policy community (not bridging science and policy as broker) cannot consider integral system theory in which scientific information can be input at many levels, assuming we encourage the sciences to develop it.

Value of Nature and Information

It is common for us to undervalue nature, not gather information indicative of a future problem, and thus overlook important actions until there is a crisis. In the history of oil spills, laws to protect the environment have been difficult to pass against short-term economic motives that discourage information about the real costs of complacency. Even after a disaster we often fail to evaluate the long-term costs. We still have no suitable way to assess the value of 'natural capital' that is lost in ecological disasters, or the medical and psychological impacts on society. With enough time on hand, risks seem hypothetical and science can be challenged, delayed, or fragmented in the usual disciplinary manner until it can no longer comment on the overall system. Temporary collaboration dissolves back into institutional fragmentation. Here again we have ethics and policy in conflict; but also science and policy are in conflict where adequate priority is not given to developing a science capable of anticipating system complexities. And if traditional science insists on fragmentation we can also say that science and ethics are in conflict, for one might argue that, with regard to living and social systems, limiting science to a machine metaphor is itself unethical. Here is where science policy can resolve the conflict by legitimizing holistic system approaches. Again, an integral approach would require all three domains to be balanced.

A highly visible outcome of oil spill crises is litigation and punishment of the party at fault. While this has an obvious role in encouraging better safeguards in the future, it does little to correct the damage. Generally speaking, we expect the damage assessment to be applied to ecological restoration, but options after the acute phase of the spill are quite limited. Furthermore, science has not provided a means for assessing the depletion of value in natural terms, and in past spill litigation some of the most ludicrous assessments have been made, such as consulting a laboratory supply catalog to add up the price of the killed organisms; which is hardly sufficient for restoring them. Requiring improved training and preparedness as part of the damage assessments may also be ineffective without the right social and political climate for long-term monitoring. The SOR Team participated in evaluating Alyeska's extensive response capacity for oil spills in Prince William Sound. However, when the Exxon Valdez went aground ten years later, very little of the originally planned response, let alone recommended improvements, was operational. In the intervening years, with a new administration, far less pressure was placed on the oil industry to maintain preparedness.

Clearly our perception of value is subject as well to anticipation of crisis and competing interests. The effect of a crisis to demand attention does not exist in the intervening times, unless there are other social drivers to maintain it.

Organization and Learning Models

"Thinking on your feet" was both a requirement and a cultured habit among SOR team members. With experience it became an instinct. The team's chemist, James Matson, for example, was widely thought to carry an hour's worth of slides in his coat pocket at all times, for any impromptu presentations. In crisis science it goes without saying that the team is open to learning from the 'bottom-up' as well as being directed from the 'top-down'. The team had to be fully open and immediately responsive to both. Strict adherence to practiced procedures was essential for safety and for gathering reliable data; and yet new information could change the priorities and the questions in a moment. That too is unusual in everyday science and most institutions.

The idea of balancing top-down and bottom-up drivers is now being promoted as a mainstream concept of corporate and government management. Many institutions seek to follow the model of Peter Senge's "Learning Organizations", which are:

> "*…organizations where people continually expand their capacity to create the results they truly desire, where new and expansive patterns of thinking are nurtured, where collective aspiration is set free, and where people are continually learning to see the whole together*." (Senge 2006)

Learning organizations are a balance between authoritative direction, largely built methodically on past experience in disciplinary and compartmentalized modes, and unstructured creative innovation from any level in the organization. The two together result in a continual learning and re-design process at the institutional level (Gharajedaghi 1999). The crisis science team was an explicitly sanctioned participatory learning activity that directly interfaced with top-down command and control structures. It was also sufficiently 'out of the box' that it could affect established systems that would be unmovable otherwise. As such it was an unintended example of participatory action research; the point being that it was highly successful.

But if we compare that situation with the more everyday scenario of a scientist trying to budge policy, it becomes clear that the policy level listens to the science mainly when it is pushed by uncertainty, well beyond the normal comfort levels for decision-making. Otherwise the process is a much slower diffusion of information, often with introduced biases. The point of Senge's proposal is that our everyday institutions need to institutionalize components that are officially less sure of themselves and open to re-organization. Like ecosystems, if organizations are complex they will survive; and if they can anticipate change they may find even better ways of operating. Presently, the US Government is cautiously proposing that its agencies adopt Senge's approach. Interestingly, the first are those with perhaps the highest stakes, for example the nuclear Navy, which has a history of being at the forefront of management models.

Public Engagement

In the case of oil development research in general, and the SOR Team specifically, funding came from tension between two unstoppable forces – political and economic desire to develop oil reserves, and equally powerful public desire to protect the environment. Without the opposition of these forces, none of the research described here would have taken place. In the United States the public is generally informed and involved in environmental issues. US Citizens have the idea, as legislated, that public lands, seas, and resources belong to them, the public. So, many decide to protect it and enjoy it, sometimes vociferously. This attitude became extremely helpful during oil spill crises, as many local citizens volunteered to help with cleanup efforts and to provide often critical information and expertise as ad hoc ‘citizen scientists’ (Irwin 1995). In many developing countries, especially those that have been dominated by foreign rule for long periods, people may have been robbed of the feeling of ownership of the land. It is then more common to focus on the inside space of one's residence and person than the outside that one has no authority over.

Ironically, India may fall in this category as a result of foreign rule, despite its famous historical examples of community protection of nature (Chhabra 2007; Tobias 2013). Today there are many "sacred groves" in India, from which we learn that one of the most effective forms of biodiversity conservation turns out to be religious belief. But sacred groves are equally vulnerable to cultural erosion if, for example, they are encroached upon to the point where the sense of value and ownership is lost (Gadgil & Chandran 1992). One key to re-establishing a healthy environment in such countries might be to rebuild the sense of public ownership; to help people become informed and involved in both use and restoration of the land and sea scape. Protection requires agreement of all four domains in the framework introduced above: ethics, science, policy, and their collective realizations.

Are we Heading Toward Global Crisis?

Only the briefest review is needed here, in which we note that human domination of the Earth may be accelerating toward a crisis (Vitousek *et al.* 1997). Presently carbon dioxide levels in the atmosphere and fixed nitrogen levels in the biosphere have been doubled over natural levels by human activity. Human production and use of fixed nitrogen in the form of agricultural fertilizers currently equals the natural production, overdriving the ocean ecosystem where nitrogen concentrates in the discharge of rivers (Vitousek 1997; Matson, Lohse & Hall 2002; Lambert & Driscoll 2003). Nitrogen runoff is creating large 'dead zones' offshore and deltas themselves are disappearing globally from a complex of causes altering their dynamic stability (Huh & Coleman 2004). We can chronicle similar effects on the rivers of the planet, as water becomes almost completely diverted for human use. Rivers are dammed for water and power to such an extent that many major rivers barely reach the ocean and potable water is becoming a scarce commodity in many regions (Millennium Ecosystem Assessment Board 2005). Species on Earth are being driven to extinction at a rate equal to or greater than any extinction event in geologic history. Total extinctions are approaching 30-50% of pre-industrial numbers (Barnosky *et al.* 2011). Species are disappearing faster than we can catalog them (Dubois 2003). With changing climate, species ranges must shift, and with global use and fragmentation of the landscape there are few corridors for migration and less places to migrate to. Fully half of the Earth’s usable land surface is now converted for human use. All of these changes are part of a global system with feedbacks between them that we don't understand.

The Fifth Intergovernmental Panel on Climate Change has issued the strongest statement yet that human activity is causing temperatures to rise in the Earth system adding energy to storms, changing weather patterns, and impacting availability of critical global resources in complex ways (Stocker *et al.* 2013). While the common person may not see the significance of a few degrees temperature rise, the problem is not temperature but heat. More heat means more energy in the ocean-atmosphere-landscape system. That energy drives global circulation patterns, establishing regional climate differences, and it drives storms. The heat must escape from the surface of the

Earth to space, which increases convection. That means an increase in the number and severity of storms and greater variation in the path of storm tracks; in other words, changes in the climate of whole regions affecting agriculture and natural biodiversity. While a potentially major rise in sea-level from glacial ice melt should happen slowly over many centuries if it follows historical patterns, the rise in sea level due to thermal expansion of the ocean, though much smaller, is more immediate and adds significantly to the destructive power of severe storms. Seasonal changes mean we are now seeing ice-free passages around the North Pole and possible melting of the Greenland ice, which drives the extremely important global oceanic circulation ("conveyor belt") between the Atlantic and Pacific, determining maritime and near-shore environments. In times of environmental change, biodiversity generally declines until ecosystems can re-organize.

The effect of these changes on the world's ecosystems and their related goods and services on which humanity depends, is largely unknown because it is a highly complex interaction. Much of the effect of climate change on humans will be concentrated on coastal areas prone to storms and flooding and marginal ecosystems that are dependent on seasonal patterns such as monsoons. Often there are societies living on the edge of human requirements in these areas. Human fragmentation of the landscape fixes specific land uses in a given location. This reduction in capacity for geographic responses to climate change drives species extinction and forces human systems to operate sub-optimally, or even in conflict possibly leading to war. Human factors, even shifting economic and value systems, thus have a major contextual effect on landscape dynamics, with complex feedbacks between the two.

The Millennium Ecosystem Assessment (Millennium Ecosystem Assessment Board 2005) 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. We especially do not understand bio-environmental feedbacks, socio-ecological relations, and place or species based natural values. Counter-assessments (e.g., (Lomborg 2001) challenge these views politically, and to some degree ethically, and apply different contextual meanings to often the same facts, to claim that human prosperity has generally been increasing and should be allowed to benefit from technology. Both views may be correct: Human prosperity may be increasing at the cost of natural capital with results we cannot precisely know. Present ecological science and informatics is only beginning to explore definitions and tools to record what the trends mean for wellbeing or to allow us to assess the proper balance between the benefits of technological and economic advance and the costs to natural systems (e.g., Bakkes *et al.* 2007). Meanwhile, these opposing assessment measures are not comparable in science or policy analysis because they reflect entirely different value systems. A more holistic science is required to contrast them in a meaningful way, and to study how they are related. A significant new effort to study crises as they happen, with embedded science, may be the only practical way to improve our capacity for understanding whole system behaviors; for outside of crises we do not approach the problem as a whole.

A Multi-Cultural and Pre-Historical Perspective

There may also be lessons we can infer from ancient history. A simple accounting of global land use change over the past 5000 years (**Figure 10**) shows extremely sudden global domination in modern times (Kaplan *et al.* 2010). Yet on the scale of human lifetimes these changes have seemed to be gradual enough for us to accommodate to them with naive optimism, not really knowing the consequences. In our age of science and technology we live by faith in the benefits of development: Humanity on Earth is a grand experiment.

And yet there seems to be a paradox in that human productivity is racing to greater heights while our ability to serve human and natural needs is falling behind. This disparity suggests perhaps a false hope placed in technological development and its presumed economic and social benefits. Human values do not necessarily improve with technological advancement, but instead need to be cultivated in their own right. The country of Bhutan became iconic for representing human values by creating a measure of "Gross National Happiness" (GNH); which became the catalyst for ambitious environmental policies (Bates 2009; Tideman 2011; Chhetri 2011). Not surprisingly human happiness is closely tied to ecological health and natural beauty, but aside from Bhutan's encouraging example, the connection between national prosperity and human well-being is rarely made.

It would not be reasonable to expect humanity to willingly return to the less technological life styles of native or ancient societies; nor can anyone say that would be a good idea. But we may be able to learn principles from those societies in the same way that we can extract lessons from crises. We need to study holism in any form that it occurs, or has occurred, and especially we need to know how to achieve it in a new way that is integral with modern technology and across cultures (Ostrom 2009); for sustainability seems to require a balance between certain natural principles of systemic harmony, and technological capacity that may be required for survival.

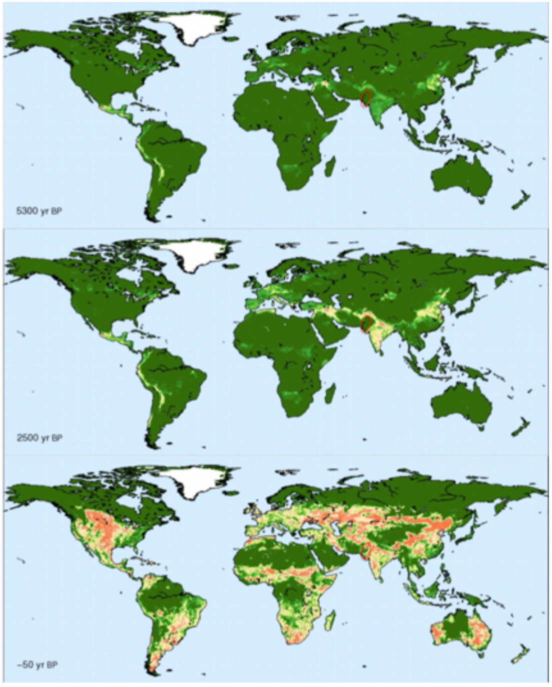

Figure 10: Landuse 3300BCE to Present from (Kaplan *et al.* 2010)

We might learn from India, for example, as perhaps the longest and most intensive case of human dominance of the landscape of any region of the world. This gives India the distinction of having produced some of the best and worst examples of conservation and sustainability. A great deal can be learned from India's rich past and highly adapted present, as a counterpoint to the environmental ethic that exists in the West from a much more recent occupation of the landscape and industries that export many of their problems to poorer lands. Neither scenario may be best for producing knowledge of whole-system sustainability and adaptation, but perhaps together they form necessary complements of it.

We also see in **Figure 10** that the Indian sub-continent was the most extensively and intensively developed landscape in the world in 500BC. But we are missing data for the Indus/Saraswati basin (red oval), which undoubtedly was also a cradle of agriculture and civilization equivalent to Mesopotamia prior to its decline around 1900BC due to desertification (Kenoyer 1997; Valdiya 2002; Danino 2010). But from as early as 3000BC this region was home to a most surprisingly holistic, productive, and un-warlike society (Kenoyer 1998, 2008; Mcintosh 2001; McIntosh 2008; Danino 2010). The story of the Harappan and Vedic civilizations, which may have been related, is being re-told today in the light of more comprehensive evidence from archaeology, geology, linguistics, paleoclimatology, and remote sensing. We mention it here as an example of historical experience with sustainability and holism as a philosophy. The ultimate demise of this civilization due to climate change, may also tell us something about the importance of adaptive technological advances; even while, ironically, our now great technological capacity to adapt has itself produced a climate crisis. The legacy of the Indus/Saraswati civilization and its lessons were buried under the sands of the Thar desert, and knowledge of its existence was equally buried, until recently, by political and cultural forces.

Sustainability Science

Many have noted that our present relationship as a species to the ecosphere is like a parasite to its host. Environment and resource policies address isolated or single-resource issues aimed at optimizing goods and services for an increasingly demanding and expanding society. As with any parasite, it is in our interest to create a less virulent disease in the host, and so it is most common to address sustainability science in just that way; how to maximize human systems without doing irreparable damage to the host. Even the US National Science Foundation's definition of sustainability is a statement of policy, not science, that naively adopts that perspective. It reads:

> *"A sustainable world is one in which human needs are met equitably without harm to the environment, and without sacrificing the ability of future generations to meet their needs." (NSF SEES Program)*

This statement was considered novel at the time of the Brundtland Commission report from which it was taken (World Commission On Environment and Development 1987), but perhaps today, 28 years later, we might consider a more progressive approach. We have yet to define the science of sustainability, or to visualize humanity's presence on Earth in a beneficial light with regard to the whole system. If biologists are correct, even a primitive bacterium has done better. Most experts believe that mitochondria evolved from a parasite that established synergy with its host, thus launching Eukaryotic organisms to unimaginable advances. Principles and scientific explanations of whole-system behavior are not necessarily restrictive. They can include new creative ways of working with nature, as in the new visionary field of "bioneering", which takes an optimistic view that more natural solutions to our problems can lead to new unimagined possibilities for humanity and nature (Ausubel & Harpignies 2004; Ausubel 2012). These developments may be changing both the industrialist and the naturalist dialogs.

'Sustainability' thinking in the past was about 'process sustainability'; that is, how to sustain processes such as resource exploitation, as with the fur trade, meat production, agricultural yields, forestry, economic growth, oil extraction, etc., and get away with it. That thinking has met with survivable strategies as well as classic failures, and as a result our environmental policy has been expanded each time to consider more of the whole. Resource management has expanded its focus hierarchically from biological goods, to populations, to habitats, to environments, and to now to call for whole "Ecosystem Management", listed as a first strategic goal of national environmental agencies. Still, our experience is with managing individual processes. We are not yet asking the question of "system sustainability", which is the understanding and ability to do what is needed to have sustainable systems (Kineman & Poli 2014).

Presently, we have neither the knowledge nor capacity for whole ecosystem management, and we are instead overwhelmed by the momentum of unstoppable processes driven by economic and political forces that are often beyond the reach of local managers. The problem ranges from local effects of global environmental changes to intense problems in dealing simply with waste products. While critics would label this informal assessment of our ecological status as ‘gloom and doom’, it is factual and need not be the least bit opposed to human development if we decide to take a holistic view of present opportunities. We obviously need a means for collective problem-solving and decision-making in anticipation of crises, i.e., before we are engaged in a crisis response. This most likely means we must do the things we *would* do in a crisis, in anticipation instead of reaction; skills we might only gain, barring major cultural change, during actual crises with a focused program of learning.

Holistic Thinking

Recent attempts to address the problem of assessment through the language and concepts of *ecological economics* (Costanza *et al.* 2002) have proven helpful in some regards but, despite the field's ability to define terms and its ability to communicate with business and policy, it is still limited by its implicit reduction to a single comparative value and linear cost-benefit analysis. Ultimate incomparability of values, non-linearity of trends, and complexity of their relations, render such assessments extremely weak (Kineman 2005, 2007).

If Hardin was correct, that the incompatibility between unlimited economic growth and ultimately limited natural capacity has no technical solution, we need to enter into a new universe of possibilities for creative problem solving at a higher level than the problems themselves. System sustainability calls for a scientifically grounded whole-system framework.

The reason that science, as it developed during the modern era, paid very little attention to the nature of whole systems lies deep in the mathematics of science and assumptions made in the development of modern science in the West that excluded "higher" causalities - those pertaining to the contextual effect of systemic influences (‘final’ and ‘formal’ as we have translated Aristotle) on dynamics (Aristotle’s ‘efficient’ and ‘material’ causes). There is a new understanding in the ecological sciences that organisms and ecosystems are complex systems and that a new kind of science is needed to study them (Waltner-Toews, Kay & Lister 2008; Patten 2014;

Ulanowicz 2014), but it requires a rigorous, mathematical and naturalistic concept of whole systems that we don't presently have.

Whole-system thinking in general tends to be marginalized by mainstream science. David Bohm wrote, for example:

> *"The prevailing tendency in science to think and perceive in terms of a fragmentary self-world view, is part of a larger movement that has been developing over the ages and that pervades almost the whole of our society today ... it gives* [people] *a picture of the whole world as constituted of nothing but an aggregate of separately existing "atomic building blocks," and provides experimental evidence ... that this view is necessary and inevitable. In this way, people are led to feel that fragmentation is nothing but an expression of "the way everything really is" and that anything else is impossible."* David Bohm (Crowell 1995)

The thinking that came naturally in crisis science was *anticipatory* and *systemic.* It necessarily required a broad system perspective to consider many future possibilities. Global change science is also anticipatory. Its whole-system approach was inspired by images of the Earth from space that clearly planted the idea with us that the Earth is one system, with mutual relations and pathologies; in one sense fragile, and in another sense incredibly robust and creative. We were humbled but also inspired by a conscious blue jewel adrift in the darkness of empty space; which is our home. We also saw, for the first time, a synoptic view of large-scale weather and climatic patterns. It was thus climate scientists who almost miraculously created the global "System Science" programs (Earth System Sciences Committee 1988). There was great resistance to classifying climate change and ecosystem degradation as crises, either globally or regionally, and a strong political lobby argued that they are apocalyptic fantasies. But through the efforts of the IPCC to establish facts, and characterizations like Glantz's creeping environmental change, the case is being made that home is both a place that will care for us, and a place we need to care for.

The question here is if a strong long-term vision of the future can do, from human intentions, what crises cause us to do from instinct. Can we learn and apply the characteristics of integral science learned from crisis research, to understand and manage complex systems before we are forced to?

The Role of Business Leadership

As "Sustainability Science" emerges with a stronger emphasis on theoretical understanding of complex systems and their management, it may begin to balance strictly heuristic and summary models with deeper theory. We have discussed two kinds of sustainability: "process sustainability" and "system sustainability". The first represents most current work and deals with maintaining critical processes that supply human needs, as currently perceived; whereas the later asks what properties a system must have for it to be generally sustainable – what perhaps we may need to do differently to be sustainable. The former is more related to policy than science, the role of which is merely to establish limits. It tends to be confrontational, lacking theoretical solutions. The second is theoretical, requiring a deep scientific understanding of how systems work. It has much in common with the lessons of crisis science discussed here. But its lack of an accepted theoretical framework leaves it largely ignored.

Most experts and governments are now widely agreed that humanity must learn how to live in harmony with nature, or suffer great losses in the near future. In this science we want to do more than react to crises; more than mitigation and restoration. We want to develop an anticipatory science that will look forward and foresee both problems and solutions for a better future, remembering that 'system sustainability' is ultimately about integrating natural and human values for more than sustainability, reaching optimistically toward "thrivability" (Laszlo 2014). We must appreciate the irrevocable effect of present actions on future values. One iconic picture of four French children overlooking the Amoco Cadiz spill does this well, where words fail (**Figure 11**).

Figure 11: Anticipating a Future at the Amoco Cadiz Oil Spill (Photo: Jean-Pierre Prevel / AFP)

In the mid to late 1960s, economist Kenneth Boulding and architect Buckminster Fuller helped popularize the notion that we are all passengers on "spaceship earth." According to the Brundtland Commission, an initial approach to sustainability might be "running the global environment – Earth Inc. – like a corporation: with depreciation, amortization and maintenance accounts". In the book "*What Next? Surviving the Twenty-first Century*" Chris Patten makes the now standard argument that while nature recoups its losses up to a point, we nevertheless need to watch our natural account balance to avoid a life-threatening overdraft:

> "*In other words, keeping the assets whole, rather than undermining your natural capital... a sustainable business meets the need of the present generation without compromising the ability of future generations to meet their own needs or which does not leave behind a mess that is impossible to clear*" (Patten 2009).

Gaylord Nelson, former Senator in the USA and founder of the first Earth Day events said on April 22, 1970:

> "*The economy is a wholly owned subsidiary of the environment, not the other way around. All economic activity is dependent upon that environment and its underlying resource base of forests, water, air, soil, and minerals. When the environment is finally forced to file for bankruptcy because its resource base has been polluted, degraded, dissipated, and irretrievably compromised, the economy goes into bankruptcy with it.*" (see (Nelson, Campbell & Wozniak 2002)

This vernacular economic language is meant to communicate a very important message in the most basic understandable terms. But even this lesson in holistic accounting, limited as it is to host-parasite strategy, seems to have fallen on deaf ears of the world's political and business leaders. And yet we have the even greater challenge to develop a scientific and social sense of holism that is much deeper than balance sheets and other economic metaphors and much more creative of futures beyond mere sustainability. But we do have to start with a model of leadership that is based in conservative ethical norms, such as: "*The earth provides enough to satisfy everyone's need, but not everyone's greed*" (Gandhi 1958). For long, businesses have operated on the paradigm of economic growth as the lone indicator of success. The time has come to create new paradigms that can simultaneously focus on the triune of economic, social and environmental sustainability. In anticipation of any crisis, the first priority is to stabilize the situation, then to look for opportunities to turn disadvantage into advantage – to engage our creativity.

Again we can look to Bhutan. It was during the 1980s that Bhutan's former King Jigme Singye Wangchuck decreed that his government's success must be evaluated by how happy the people become instead of how much the economy grew as measured by Gross Domestic Product (GDP). Promotion of sustainable development, environmental conservation, preservation and promotion of cultural values and the establishment of good governance are the four key pillars for Gross National Happiness. A new Bhutanese constitution came into being with the first elected democratic government in 2008. The now Prime Minister, Thinley Jigmi Y Thinley, is a vocal proponent of Gross National Happiness and environmental protection. In terms of environmental management, the Bhutanese constitution maintains that 60% of Bhutan's total land shall be kept as forest cover "for all time". The country has actually increased its forest cover from 45% during the 1960s to 72% today. Bhutan has also declared internationally, at the Copenhagen climate talks, that it would maintain permanent carbon neutrality. Significantly, the Bhutanese prime minister has said, "*Climate change is the result of our way of life that is driven by insatiable human greed. Our GDP-based economic development models, founded on the notion of endless growth, have promoted consumerism and materialism with little consideration for cultural and ecological costs*" (Chhetri 2011).

Business has several important roles to play. First, corporations under their own initiative can shift their internal policies toward mutual benefits to society recognizing not only short-term gains but also long-term likelihood of gains from a more stable society. Since corporations have a major influence on government policy, they can lobby for a more level playing field where good practices will not result in others taking advantage. Finally, with government support, corporations can become part of the solution by engaging in long-term research into new 'win-win' technologies, tapping human capital before we deplete nature's capital. Part of this shift is to eschew policies based solely on quarterly earnings guidance, which tends to result in decisions that may be contrary to the corporates' own enlightened self-interest as well as to the interests of society in general.

Local and national business and policy is not generally an exception to the way international corporations have been self-interested in destructive ways. However, there are a number of shining corporate examples of a better way. India's unique past and ancient ethos of holism, for example, survives today in many official places and in the memories of many people. For example, Tata Corporation has a tradition of donating 70% of its profits to charities and has a policy to place the well-being of employees first in their strategic plans. Not only has this not weakened the company, which competes successfully in the open marketplace; but it gives employees a sense of pride and ownership. In the USA the actor Paul Newman, who passed away only weeks before the 2008 global economic crash, had started "Newman's Own"; a for-profit corporation that donated 100% of its profits to charity. Not only has the company thrived since its start and through the recession, but it provides a four-way win, for shareholders, employees, customers, and charities. Its for-profit status allows it to contribute to a wider variety of charities than even a non-profit is allowed to, and also to raise money from a wider variety of products. There are many more innovative business models emerging that may find new ways to support both Man's and nature's intrinsic balance of sustainable practices. Generally speaking, the management community is waking up to a fact that ecologists have overlooked; that natural sustainable systems, and therefore businesses, are "learning organizations" (Senge 2006) that balance creativity with tradition to not just preserve their market share, but to thrive through anticipatory actions that foresee a larger reality.

CONCLUDING REMARKS

Crises trigger holistic thinking in terms of interdisciplinary knowledge, institutional collaboration, and individual cooperation. Science in a crisis follows a very different philosophy than we pursue in normal science and institutional structures; one that is integrative, creative, and very much a 'learning’ organization of science and society for a brief time until returning to disciplinary modes. Our challenge is to anticipate environmental or ecological crisis before we are forced to by personal impacts. The positive message from this analogy is that developing the means for pursuing more holistic science and scholarship may not be as difficult as might be imagined, if we pattern our approach after natural capacity we already have.

We should be able to see, from the multitude of recent developments at the forefront of mainstream science and system thinking, that the era of exclusively mechanistic thinking is drawing to a close. It will not be extinguished or even diminished, but it is likely that a new layer will be added to re-integrate it with the rest of nature and human experience. That layer, we believe, will be developed from current system and complexity theories combined with multi-cultural studies of holism both present and past; and we believe it will expand science itself. Global society may, as a result, enter an "ecological renaissance" in the coming decades, as we wake up to more whole thinking.

Most authors in Sustainability Science cite the need for a holistic integral framework for science, philosophy, and humanistic disciplines. They also cite many barriers to achieving such a unity of knowledge; and yet it is not well recognized how severe these barriers are, or how deeply rooted they are in our culture and scientific worldview. As a result, even proposals for a more integral approach tend to be partial, summative rather than integrative, and generally incomplete. This paper presents a pathway for combining many existing frameworks according to a perennial unity that has emerged in many fields and disciplines since ancient times. As we show, it is not at all far from our grasp, being a natural mode of interacting with our surroundings that reveals itself most in times of crisis.

However, neither the West, in its mechanistic tradition, nor the East in its own pursuit of Western ideas despite cultural memory of a holistic past, has yet articulated theoretical or practical holism and system sustainability in a form we can widely apply. Current dualistic models require expansion to attain much greater completeness, while attempts to recapture ancient or indigenous holism require interpretation and encoding into modern terms with mathematical rigor that itself requires more expanded views. It is likely we can construct those views from new beginnings in Category Theory, but only the raw beginnings of such a new science and informatics can presently be outlined. A great deal of work needs to be done, but the early signs are hopeful.

We can take some very important additional steps by establishing a global research and education agenda that will help East-West and North-South dialogues explore rigorous whole-system thinking. The main step required in this is to legitimize the question “what is a whole system” in current science. The global agenda should not be just a concept, but a genuine program of research and collaborative multi-cultural education involving integrative learning techniques (Blair & Caine 1995) and integral frameworks. We should aim for it to emphasize cross-disciplinary, cross-cultural experiential learning through *in-situ* problem solving facilitated by theoretical research, open dialectic and student-driven topic research, perhaps also in the sense of Senge's "Learning Organization” applied to society.

Additionally, recognizing the difficulties intrinsic to establishing holistic research in its own right and the value and similarity of focused research during a crisis, as reviewed here, we strongly recommend significant national and international funding toward establishing “Crisis Science” in educational and governmental institutions through partnerships that allow university Crisis Science teams to learn intensively during crises, with necessary training and support. It is reasonable to build such research teams within existing interdisciplinary institutes that are focused on socio-ecological system sustainability more generally.

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