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Earth Systems Engineering and Management as Governance

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Abstract

Earth Systems Engineering and Management (ESEM) is a framework for both discussing and addressing the adaptive management of complex socio-ecological systems (SES). Governance of emerging technologies is an SES challenge that demonstrates all the classic symptoms of a wicked problem. This paper surveys governance literature in light of the ESEM principles and explores the potential for using the principles of ESEM as a mechanism for governance, addressing particularly ESEM's overlap with the recently promulgated *anticipatory governance* as defined by its three pillars of foresight, engagement, and integration. This paper demonstrates that the intersection of these concepts is significant and concludes that ESEM is a worthy framework for governance.

Introduction

Allenby (2000) defines Earth Systems Engineering and Management (ESEM) as:

> [T]he capability to rationally engineer and manage human technology systems and related elements of natural systems in such a way as to provide the requisite functionality while facilitating the active management of strongly coupled natural systems. ESEM also aims to minimize the risk and scale of unplanned or undesirable perturbations in coupled human or natural systems (p. 15).

Human technology systems are complex. Since human technology interacts with natural systems at a global scale, it becomes impossible to separate the resulting "earth systems" into natural and human components. Hence, earth systems are complex socio-ecological systems comprised of many interconnected agents exchanging information, influence, and involving feedback pathways that make it difficult to distinguish clear cause and effect relationships. As with all complex systems, an earth system's response to inputs is non-linear and frequently counter-intuitive, characterized by emergent features and properties that illustrate how the whole can be more than the sum of its parts. Further, earth systems demonstrate significant temporal and spatial discontinuities (e.g., uncertainty, time lags, and disjointed, seemingly random effects) and operate far from equilibrium in a state of constant adaptation to changing conditions. In addition to exhibiting emergent characteristics, earth systems evolve over time, altering their capabilities, impacts, and extent (Allenby, 2005).

With or without humans involved, earth systems are complex. Admitting to the human elements in such systems makes them wicked-complex. Wicked problems are summarized by Rittel and Webber (1973) as follows:

1. They defy definitive description;
2. There is nothing like an "indisputable" public good (i.e., public value);
3. There are no objective definitions of equity;
4. Policies that respond to such problems cannot be meaningfully correct or false;
5. It makes no sense to talk about optimal solutions;
6. There are no "solutions" in the sense of definitive, objective answers.

When every individual's model of the problem is different, and when analogies abound and are constantly debated, it is safe to assume the system is exhibiting wicked-complexity. When there is significant polarization in public opinion and when shared values cannot be agreed upon, the problem is wicked-complex. When resource allocation and sharing is being argued and there doesn't seem to be a way to garner consensus on what is fair, wicked-complexity is lurking. When the extremes in the solution space are taken out of play, and there are no meaningfully correct or incorrect approaches, the problem is wicked-complex. When ultimately it must be acknowledged that there are no solutions, let alone optimal ones, the problem is wicked-complex.

ESEM has been proposed as a framework for addressing the management of wicked-complexity. ESEM fully acknowledges and embraces the wicked-complexity of the problem-systems it purports to manage, and in fact, since such wicked-complexity is of human origin, ESEM strives to take full responsibility for them. As Allenby says, "ESEM can be seen as the acceptance of responsibility for the ethical and operational implications of what the human species has already been doing for centuries, and is continuing to do at a rapidly increasing rate" (Allenby, 2000, p. 13).

While ESEM principles were originally proposed as a mechanism to guide adaptive management of complex human-engineered systems at their intersection with natural systems, this paper proposes application of the ESEM framework be extended to include potential use in the governance of emerging technologies. This proposal is fortified and exemplified herein with a survey of and comparison to extant governance literature—outlining conspicuous overlap and identifying areas where ESEM has surpassed proposed governance frameworks. This comparison constitutes the primary purpose of this paper and results in establishing the ESEM principles as a credible governance framework.

Of course, defining *governance* is not necessarily a simple matter, with each individual scholar adding important nuance. For our purposes, Roco (2006) provides a solid (and mature) definition of governance:

> Governance includes the *processes*, conventions, and institutions that determine: how *power* is exercised in view of managing *resources* and interests; how important decisions are made and conflicts resolved; and how various *stakeholders* are accorded participation in these processes…. [Governance] attempts to set the *parameters* of the system within which *people* and institutions behave (p. 3, emphasis added).

In a nutshell then, governance involves power, processes, people, products (resources tend to require some production), and indeed, parameters. While the alliteration is interesting, the fact that these elements can be seen to combine and interact to result in complexity is more so. Governance is itself a complex earth system which could be analyzed using the ESEM approach. The point of this paper, however, is to demonstrate that the current governance literature forms a framework by which governance *is already* being analyzed and that there is significant overlap in the two approaches. Additionally, a specific framework known as *Anticipatory Governance*, with its three pillars of *foresight*, *engagement*, and *integration*, has arisen in the governance literature (Barben et al., 2008). This framework will be referenced throughout as it provides the most complete framework for governance in the extant governance literature.

A Backdrop for Governance

Prior to presenting the survey of the governance literature in light of the ESEM principles, there are several important concepts that must be reviewed. These concepts provide a backdrop—an environment—in which the governance literature swims.

First, despite the use of phrases like "governing without government" (Rhodes, 1996), in many regards, both the governance literature and the ESEM principles can be interpreted as *assuming the presence and operation of a stable and legitimate representative government* (e.g., democracy). While some ESEM principles can be effectively employed without that minimum requirement, further study would be required to determine the extent to which many of the governance scholars assume such a backdrop. In large part, it appears that the governance literature assumes a stable "government" environment in which "governance" can be implemented and tested. That is, it would seem cavalier to assume such frequently referenced concepts as "legislative policy" and "government regulation" can mean anything without the support of a legitimate government. So, while it is apparent that most authors in the governance literature do seek to unburden government, and feel that there are efficiencies to be realized through less government involvement in a "new governance" (Rhodes, 1996), it does appear that they assume government will be there, delivering rule of law, due process, and some "guarantee" of justice and the removal of the "unfreedoms" (*sensu* Sen, 1999) of oppression and fear. Where such an environment is not present, it must be acknowledged and specifically managed.

Secondly, while nation-states still exist, it is vitally important that any discussion of governance acknowledge the requirement for *international cooperation* in governing emerging technologies. This topic is only briefly introduced here as it bears on later discussion. Specifying technological trajectories is no longer a role for a single sovereign nation-state—even if one should happen to remain globally dominant. A simple testament to this fact is the growing international cooperation of social scientists who are studying "the new governance" (Rhodes, 1996). Fisher and Guston boast "students from nine universities in six nations spread across three continents" in just one aspect of their program (Fisher & Guston, 2011). If technology is emerging internationally, it must be governed internationally. Parochial policy can no longer be viewed as a successful ultimate outcome in discussions of the governance of emerging technologies. In fact, what one state accomplishes can only be viewed as an input to a much larger and more complex system of global governance (cf. Smil, 2005; Roco, 2006). And, note well, informal global consortia may or may not pay any attention to such accomplishments; neither may *they* be *paid* any attention. Establishing a legitimate body to provide global governance is a difficult, but required endeavor (Mathews, 1997; Keohane, 2011). Ethical governance will require international cooperation.

A third vitally important item that will not be directly addressed herein but that should fairly *dominate* any meaningful conversation on governance is the *economic impact* of the technologies themselves. In an increasingly global free market economy (Castells, 1996), the technological trajectory of any emerging technology will follow the money—both investments and profits—whether public or private. The best and most carefully crafted policy or regulation will tend to fall by the wayside once significant economic impacts are realized. While this tends to frustrate any hopes of true and impactful anticipatory governance (*sensu* Barben et al., 2008), it must, in any case, be considered an eventuality. If governance is to be effective, hard won policy recommendations (even those implemented in light of dramatic polarization on very sensitive issues) must not be ignored once economic value is exploited in the market. If, for example, the purpose of ELSI-like programs[1] is to “forestall adverse effects associated with biotechnology” (Fisher, 2005, p. 323), then policy decisions must have teeth—and lasting impact. Fisher reminds us that “the success of a program like ELSI ultimately lies in the political will behind it” (Fisher, 2005, p. 323). And this is where we must admit our weakness in the face of strong economic returns. It will be incredibly difficult to hold back the next “killer app” whatever it happens to be, but ethical governance might just require it (Roco, 2006, p. 15).

International cooperation of legitimate governments and careful acknowledgement of economic impact are unquestionably vital domains of discourse for any rational, post-modern approach to governance of emerging technologies. If ignored, they could also serve as the most confounding factors in any consideration of governance. I will return to these throughout the discussion below.

ESEM as Governance

Allenby’s ESEM principles have no implementation order required or implied. They are all equally important, though depending on the application, they may not all be equally relevant. In fact, in keeping with the complexity of the systems they purport to manage, they all must be applied simultaneously, or severally, as necessary to analyze and manage the target complex system. In his published lists, Allenby (2000, 2005, 2007, 2012[2]) has loosely organized the principles into theoretical, governance, and design categories, but these categories will only be of limited interest in our examination of them vis-à-vis the governance literature. For our purposes herein, the principles are ordered approximately as Allenby has done in *Reconstructing Earth* (2005), but again, order is unimportant.

In the paragraphs below, limited effort is invested in completely elucidating the summary statements of the ESEM principles. In most cases the text as cited is sufficient to convey the intent. In some cases the presentation of the principle has been slightly adjusted for readability and brevity. In many cases a few short words of clarification are provided, but for the most part, the meaning of the principles will be obvious or become obvious as they are compared and contrasted to similar concepts in the governance literature. The paragraph titles are concisely stated abbreviations of the principle which are original herein. As they are not used by Allenby, any confusion they introduce is entirely the fault of this author.

Targeted Intervention

Only intervene when necessary, and then only to the extent required (Allenby, 2005).

This overarching principle is about maintaining humility in the face of complexity. But humility is not necessarily fear, and in Allenby’s economy it need never devolve into a precautionary principle which purports to delay intervention until specific guarantees can be made against all harm (Foster, 2002). Delaying intervention until full knowledge is available is not the intent of this principle. While complex systems are very unpredictable and should be handled with

[1] This refers to the Ethical, Legal and Social Implications (ELSI) program of the Human Genome Project. See *genome.gov/10001618*.
[2] *The Theory and Practice of Sustainable Engineering* review based on preprint proofs.

care, this doesn't mean that they should never be adjusted. Due diligence should be practiced, however, because sometimes the status quo is better than the unexpected results of an ill-reasoned adjustment.

For example, on one hand, Roco might be tempted to espouse a precautionary principle, in light of potential dangers of an out-of-control nanotechnology initiative:

> Given the opportunities, there is the danger that necessary risk governance precautions will not be taken internationally in the race to gain economic advantage and to grasp the economic benefits. Such an oversight could lead to an international backlash in emerging technologies development and diffusion if, due to lax standards and practice, an incident with negative repercussions on human health or the environment occurs. Given the high potential for social amplification by the media, such an incident could trigger worldwide attention and increase public concern. (Roco, 2006, p. 15).

This hypothetical situation highlights the aforementioned need for international cooperation and care in managing economic impact. If international cooperation is strong, and the risk is great enough, global implementation of a precautionary principle is perhaps a worthy intervention of *the extent required*. After all, if everyone stops, or slows down, then nobody is falling behind. Allenby, of course, would be the first to highlight such naïveté while reminding us of all those governing bodies (both recognized and unrecognized, like terrorist groups) who declare themselves "exempt" from such international cooperation.

On the other hand, Roco is sanguine about the progress being made by such groups as the International Risk Governance Council (IRGC) in outlining criteria for assessing and managing risk (Roco, 2006, p. 15). He and Allenby would agree that such criteria are a vital step in helping to determine when, and how much, intervention is necessary on a case-by-case basis.

This principle also touches on the first pillar of anticipatory governance, foresight, which includes disciplines such as forecasting and scenario development, and specific tools of industrial ecology like consequential life cycle assessment (LCA, cf. Tillman, 2000). While forecasting falls more in the arena of predicting the future based on, for example, deep knowledge of proprietary corporate goals and investment plans (as done in traditional technology road-mapping exercises), the concepts of scenario development (exploring alternative futures), back-casting, and LCA can provide quality inputs for determining what interventions might be necessary and how far they should go (Barben et al., 2008, p. 985-6). In this regard they are close in spirit to this first principle of ESEM.

Evaluate Technological Fix

Major shifts in technologies and technological systems should, to the extent possible, be evaluated before, rather than after, implementation of policies and initiatives designed to encourage them (Allenby, 2005).

After the caution of the first principle, this principle suggests that any proposed perturbations to the system must be explored before they are adopted and implemented. Sometimes thought experiments are adequate, other times more formal modeling is required, but we must perform due diligence before we adopt new approaches. Much can go wrong if we dive in without testing the waters, these are, after all, complex systems.

However, it is a well known axiom of (at least) Western culture that we are enamored with the "technological fix" (Douthwaite, 1983; Rosner, 2004). Frequently "fix" can be taken two ways. First, we find ourselves "high" on technology; we want it like a junkie wants drugs. We are, as Neil Postman said, "amusing ourselves to death" (Postman, 1985). Secondly, we fully expect it to solve all our problems. And, if a new technology promises to solve one of our problems (usually one we created with another technology) then we are usually willing to ignore the warning of this ESEM principle and adopt the technology wholesale. In our pride, we forget to assess the risks (see *Targeted Intervention*) and step into unknown territory.

Sarewitz and Nelson (2008) provide an interesting commentary on our penchant for adopting the technological fix. In a three step process which might as well have been custom-developed to respond to this ESEM principle, they suggest we perform three tests before adopting a technological fix. First, they say "the technology must largely embody the cause-effect relationship connecting problem to solution." Based on what we know about complex systems, we know that is nearly never the case. Complex systems have highly non-linear responses and seldom exhibit obvious cause-effect relationships. This means Sarewitz and Nelson's first test cannot help us. They then suggest "the effects of the technological fix must be assessable using relatively unambiguous or uncontroversial criteria." In responding to this proposal, the definition of wicked problems must be remembered. Wicked problems are, by definition (see above), difficult to describe and their definitions are seldom agreed upon by all contributing parties because of the variety of ways in which each draws their boundaries (see *Real-World Boundaries*). If "unambiguous or uncontroversial criteria" are required, then this proposal does nothing to contribute to our decision about whether a technological fix is appropriate. Finally, they propose that "research and development is most likely to contribute decisively to solving a social problem when it focuses on improving a standardized technical core that already exists." Of course, "improving a standardized technical core" simply means making well-understood, incremental adjustments to a known baseline. This is, finally, a useable evaluative technique that, unsurprisingly, matches another ESEM principle (*Incremental and Reversible*). While not a universally true axiom, incremental changes can generally be evaluated before they are implemented because they fall into our ability to visualize and/or model outcomes.

If, however, *major shifts* in technological systems are required (*sensu* Allenby), they very likely must be rolled-out piecemeal and with thorough testing as each alteration makes incremental changes to the well-established baseline. Obviously, such changes and their impacts must be measurable. This is discussed more below (see *Incremental and Reversible* and *Quantitative Metrics*).

Real-World Boundaries

ESEM requires a systems-based approach, with analysis and boundaries reflecting real-world behavior and characteristics rather than disciplinary or ideological simplicity (Allenby, 2005).

The way problems are stated defines the systems involved. Accordingly, ideology will often be implicit in the way problems are defined, rather than explicit. Boundaries drawn in ideological terms result in oversimplification and do not reflect real-world couplings and linkages through time (Allenby, 2005).

It is critical to be aware of the particular boundaries within which one is working and to be alert to the possibility of logical failure when one's analysis goes beyond the boundaries (Allenby, 2007).

With this principle, Allenby highlights the important fact that much system boundary work occurs *before* lines and boxes are drawn on a system diagram. Importantly, Allenby acknowledges that system definition starts with the problem statement, and that the problem statement will almost always be value-laden and ideologically driven. So while appropriately selected system boundaries are essential to successful problem solving, our tendency to draw them "in ideological terms" must be recognized. Only when all points of view are considered can real-world boundaries be scrupulously architected. This implies that the posture we assume while formulating our system boundaries is at least as important as the ultimate boundaries themselves. Cash et al. (2003) highlight the challenge and point out that "boundary work" is a significant scholarly discipline:

> A wide range of studies have identified the importance to effective science advising of ''boundary work'' carried out at the interface between communities of experts and communities of decision makers. This work highlights the prevalence of *different norms and expectations* in the two communities regarding such crucial concepts as what constitutes reliable evidence, convincing argument, procedural fairness, and appropriate characterization of uncertainty. It points out the difficulty in effective communication between the communities that results from these differences, and stresses the importance for effective advising of explicit development of boundary-spanning institutions or procedures (Cash et al., 2003, p. 8086, emphasis added).

When they speak of the "different norms and expectations" held by different communities, they reinforce Allenby's concern that ideology often leads to mismanaged boundary delineation and is hence implicated in system failures. (Note that boundary work at the interface between experts and decision makers in the public policy domain is specifically what Roger Pielke, Jr. addresses in his book, *The Honest Broker*, to which I will return later). The differing norms are real, and so must be the boundaries. Further, to prevent misunderstandings across the boundaries, Cash et al. recommend "explicit development of boundary-spanning institutions or procedures." Such procedures allow for Allenby's "logical failure" to be avoided. What is important here is that sometimes it is assumed that boundaries and disagreements should be "smoothed over" and made invisible, but this is not the case. As Cash et al. and Allenby demonstrate, ignoring the problem does not make it disappear.

Stoker (1998) suggests that *governance* "refers to the development of governing styles in which boundaries between and within public and private sectors have become blurred" (p. 17). Later, he proposes "blurring of boundaries and responsibilities" (p. 21). But the careful reader will realize that he *cannot* be suggesting that we leave the boundaries undefined. Instead, he is suggesting they might be allocated differently than they have been in the past. Boundaries are vital—but arbitrary. And in the ESEM framework, "arbitrary" is not a pejorative word. It means it is "design space." As Allenby points out, *real* boundaries *must* be drawn; flexibly to be sure (see *Incremental and Reversible*), temporarily perhaps, but nevertheless definite. This is the nature of complexity. Just because it can be difficult to discern, does not mean a boundary can be murky or ill-defined.

The real boundary must be drawn to ensure that all primary actors have entered a dialogue. If there is anything that is foundational to the ESEM approach, it is that dialogue is paramount (see *Multi-dimensional Dialogue*). Roles don't change dramatically, but understanding of the responsibilities of each may. For example, for the actors involved in a discussion of the public understanding of science (cf. Rayner, 2004), the scientist will still do the science, but it will be done in such a way as to facilitate the dialogue with the other actors and not to simply cloister him to do what he loves. The boundary will be obvious and definite, but still accessible for dialogue. The scientist who says "the public cannot understand" is the scientist who has not worked hard enough at boundary-spanning. The scientist who says "I must work alone" is the scientist who has broken his contract with the public (cf. Guston, 2000). Likewise, a public that cannot afford a scientist some "space," or that demands science must be done "this way" or "that way," is a public which dishonors the scientist's craft and has thus damaged the dialogue.

And dialogue, it seems, is something at which journalists might excel. Perhaps this is where journalists and the media contribute most constructively. We must honor their skills too, and scientists and public must be willing to enter the dialogue. In a recent *Science* editorial, Christopher Reddy (2011) employs conciliatory language in discussing the relationship between science and the media. He's doing boundary-spanning work. He wonders how science can "engage" the media. He recommends scientists invite reporters "into a conversation about the challenges that both parties face." He suggests they "reach out" and "learn each other's languages." These are all steps in the right direction. While his editorial might be criticized for leaving the public out of the loop, such a critique would be premature. First, recall that the media is also a *public*. Second, the media is a very special public with skills that can be exploited in improving the public understanding of science; skills that are useful in boundary-spanning.

In a twist to Reddy's thoughts not mentioned in the governance literature, this could also be a point of interface for the *anticipatory governance* pillar of *integration* (cf. Barben et al., 2008, p. 988). Social scientists seeking to integrate themselves into the laboratories (Fisher & Guston, 2011) could do more than shadow scientists and cause them to be more reflexive in their approach to science. Instead, as *publics* themselves, they could serve to build a bridge between the scientist and the public-at-large by developing high quality, easily accessible literature about the science and about the approaches used in the laboratory. This could be done at both a deeper and broader level than can be accomplished by a journalist suffering from deadlines and editorial sensationalizing. This sort of middle-of-the-road, anecdotal, human-interest, public-service approach would go far toward making the public more comfortable with "what the scientists are up to." Such boundary-spanning work would also serve to critically connect otherwise detached social scientists to other actors in the system.

Boundaries are hard. Take that both ways. Yes, they are difficult to define and deduce, but they are also (vitally) firm; clearly delimiting roles and responsibilities. Such boundaries, however, must be flexible. Not haphazardly fluid, but adapting to change as required (see *Resilient not simply Redundant*). Boundaries are also frequently contested. What else might we expect from a complex system? In an early piece, Sheila Jasonoff indicates

> Many of the boundary disputes between science and policy are played out in the realm of language.... However neutral on their face, these terms are politically charged because they are used to explain or justify the allocation of power and prestige between the institutions of science and government. More generally, boundary-defining language not only serves the immediate interests of social and political groups, but, through the creation of new conceptual categories, opens the way for extending those interests to new or larger domains.... A study of the way these disparate interest groups use boundary-defining terms about policy-relevant science reveals their essentially contested character (Jasonoff, 1987, p. 199).

Any boundary that is used to "justify the allocation of power" or that serves and extends "the immediate interests of social and political groups," is expressly what Allenby cautions against in this principle. Boundaries must be real, must support real-world exchanges, and must not be drawn on ideological terms. Boundaries should reflect *real-world behavior and characteristics rather than disciplinary or ideological simplicity*.

Multi-dimensional Dialogue

ESEM projects and programs are highly scientific and technical in nature—but they also have powerful economic, political, cultural, ethical, and religious dimensions as well. All of these facets should be explicitly integrated into ESEM approaches (Allenby, 2005).

With his listing of this broad base of "dimensions," Allenby is clearly pointing out that values matter; values drawn from every arena of life and culture. Governance must admit to, and manage, values.

Here, the *engagement* pillar of *anticipatory governance* is in full force. Such engagement is intended to "go beyond opinion polls to more substantive engagement" (Barben et al. 2008, p. 987) and was exemplified recently with the national citizens' technology forum (NCTF) on nanotechnologies for human enhancement. This effort demonstrates the kind of extended public engagement that is required for real understanding to occur (Cobb, 2011). In short, the engagement:

- Enlisted "real" citizens,
- Provided meaningful training materials in the form of a 61-page document (note well that it was not an impenetrably daunting ~400 pages),
- Continued for a manageable, but reasonably extended period (two full weekends, plus 18 hours of moderated and facilitated discussion in between—*the number of hours in a three credit university graduate seminar!*),
- Demonstrated that expectations matter (though in this case the participants were only led to believe they would be influencing policy), and
- Paid them for their time.

It is in these extended engagements that public values best emerge, and once they emerge, it is important that policy reflects them. Note that this need not imply the policy adopted merely reflects a majority rule. Instead, the policy must deal meaningfully with public values even in light of significant polarization.

Bozeman and Sarewitz (2005) do a credible job outlining the reasons for "public failure" in U.S. science policy. Calling it "public failure" tends to make one think they are faulting the public, when in reality they are simply contrasting it to *market* failures. They define "public failure" as occurring "when neither the market nor public sector provides goods and services required to achieve core public values" (p. 122) and their first case of "public failure" is "when expression of public values is stifled or distorted" (p. 123). Clearly, policy which sides with a slim majority would serve to stifle and distort public values. Allenby agrees and this ESEM principle makes it clear that it should never be allowed to happen. Instead, all dimensions across which values form should be explicitly considered in the analysis. ESEM outcomes will rarely, if ever, take a side in a public debate, but will frequently serve to reconcile the sides.

The governance literature speaks similarly broadly about values. But Allenby's summary principle should not be construed as a catch-all for the inevitable criticism about not taking values into account. He is specifically saying we—the participants in governance—must first and foremost deal honestly with our pre-conceived notions (see *A Part of the System*). In fact, we must do this before, during, *and* after we engage the public. Macnaghten et al. (2005) suggest a significant role for social scientists in elucidating such values. According to them, social scientists are "experts in the study of public opinion" who can "help shape innovation processes" because they are "good public communicators" with a collection of "social science techniques" (p. 271). But even social scientists that purport to be involved in such public values dialogue must start with an honest assessment of where they stand on issues. Only then can it be known what bridges are required and how they should be constructed to ensure dialogue.

Sheila Jasonoff's "technologies of humility" inform the discussion here:

> [There are] four focal points around which to develop the new technologies of humility. They are framing, vulnerability, distribution, and learning. Together, they provide a framework for the questions we should ask of almost every human enterprise that intends to alter society: what is the purpose; who will be hurt; who benefits; and how can we know? On all these points, we have good reason to believe that wider public engagement would improve our capacity for analysis and

> reflection. Participation that pays attention to these four points promises to lead neither to a hardening of positions, nor to endless deconstruction, but instead to richer deliberation on the substance of decision-making (Jasonoff, 2003, p. 240).

Framing, of course, gets to boundaries, and how problems are defined (see *Real-World Boundaries*). Vulnerability overlaps significantly with Allenby's concept of resilience to which we will return later (see *Resilient not simply Redundant*). Distribution is a nod toward the complexity of the system and its interacting subsystems (also see *Multicultural Dialogue*). Learning is itself one of the principles of ESEM to which we'll later return (see *Continuous Learning*). Interestingly, Jasonoff indicates we must avoid a "hardening of positions" which also speaks about boundaries and a resistance to boundary-spanning activities, but could also apply to what Allenby refers to as "premature lock-in" and to which we will return later (see *Incremental and Reversible*). Summarizing these "technologies of humility" in a later editorial piece, she reminds us that the call for humility is "a request for research on what people value and why they value it" (Jasonoff, 2007).

Roger Pielke, Jr. adds significant insight into the public value debate. He defines four different roles for experts in decision making in *The Honest Broker* (2007). There is a role for each voice in democratic dialogue. The *pure scientist* focuses only on the scientific details and facts and has no interaction with the decision maker. The *science arbiter* knows the science but can interface with the decision maker in answering specific factual questions. The *issue advocate* reduces the scope of choices available to the decision maker by recommending specific courses of action. The *honest broker of policy options* expands and clarifies the scope of choice available to the decision maker. Interestingly, Pielke's use of the word "honest" in describing his last category is itself value-laden. With it, he tips his hand to indicate what he believes is the appropriate approach. He compounds the indication when he refers to the issue advocate as a "stealth advocate." While not specifically calling the stealth advocate dishonest, his intention is clear: stealth advocates are sneaky; honest brokers have no agenda. This, of course, is impossible, and is tantamount to saying they have no values. Still, to the extent a would-be honest broker admits to his or her biases, it is to that extent they are honest. The ESEM principle simply exemplifies a point observed by Langdon Winner (1985, p. 157), that the fact-value divide is largely a figurative construct, suitable for philosophical arguments, but generally yielding more heat than light.

Pielke points out that when values are broadly shared by a public, advice from the pure scientist and the science arbiter makes the most sense. However when values are in conflict—as they are in most political issues—then the third and fourth expert roles are employed depending on whether you want the list of options narrowed to support side-taking (issue advocate) or expanded to support dialogue (honest broker). Pielke stresses that we have choices regarding which voices inform our policy makers. The choices we make shape the legitimacy, authority, and sustainability of the decisions made (Pielke, 2007).

Techno-Social Differentiation

ESEM projects often combine technical scientific and engineering issues and efforts to change behavior (social engineering). This is not necessarily inappropriate, but every effort should be made to differentiate between the two: the discourses, political contexts, and degrees of complexity involved are quite different (Allenby, 2005).

Implicit social engineering agendas and reflexivity make macro-ethical and value implications inherent in all ESEM activities (Allenby, 2007).

The distinction between technical and social engineering is easily exemplified with an anecdote from the recent climate change debates. Assuming climate change is occurring due to excessive anthropogenic carbon in the atmosphere and consequent global warming, a technological fix might be to manufacture and deploy sophisticated carbon capture and sequestration (CCS) systems that scrub carbon from the atmosphere and bury it in empty coal mines. A social engineering fix might be to have people reduce their carbon emissions by burying their cars in those empty coal mines and riding bicycles instead. Both solutions serve to reduce atmospheric carbon, but they are very different in terms of the discourses and value implications. As a species, we have generally opted for the technological fix (see *Evaluate Technological Fix*) because we prefer to not have our "freedoms" (for example, to drive a car) restrained. Frequently, the boundaries for the design space can be set such that there are both technical and sociological fixes to a given problem. What Allenby is pointing out is that we must understand they are completely different approaches. The complexity is even greater when both approaches are employed as parts of a larger strategy.

Using another example, Collingridge (1980) speaks of the failure of the Green Revolution to meet its objectives of feeding the poor. Though his assessment of abject failure can be argued (cf. Evenson & Gollin, 2003; but see Reinton, 1973), his reasoning is in line with this ESEM principle. He suggests that this failure was because “its objective was not a technical one, but a human one.” He says what robbed the Revolution of success was “the lack of understanding of how the technical products of the Revolution interact with the society using them” (p. 15). He summarizes with “technology often performs in the way originally intended, but also proves to have unanticipated social consequences” (p. 16). The lesson he draws is that our technological understanding far outstrips our ability to understand the social impacts of the technologies we deploy. This is a feature of complexity, and this ESEM principle is warning us to pay attention to such complexity.

Transparent Governance

Conditions characterizing the anthropogenic Earth require democratic, transparent, and accountable governance and pluralistic decision-making processes (Allenby, 2007).

Acknowledging that we have already made a value judgment in selecting democracy and rule of law for our national government (see introduction), we must (1) understand our limits as we deal with the very real impacts and influences of globalization, and (2) recognize, to an ever-increasing extent, the need for international cooperation in all we do—even when our work is exclusively focused at the national level. While Jasonoff (2003, p. 243) finds the “renewed attention being paid to participation and transparency” to be a promising development in governance, it is strictly limited to the democracies who govern by informed consent. She is not referring to a dialogue that is ongoing throughout the anthropogenic earth—despite the fact that what *we* do *here*, impacts *them* over *there*.

Fisher and Mahajan (2006) demonstrate the need for transparent governance, but also indirectly highlight the schizophrenia within the governance literature over this management of the national and global divide:

> On the one hand, a steadily escalating international funding race over the massive economic and other gains projected for nanotechnology products has been used to justify an aggressive US approach to promote rapid technological development and accelerated marketplace transfer. On the other hand, heightened awareness of the role that public concerns and perceptions can play in the adoption of new technologies has occasioned extraordinary legislative language requiring research on societal concerns to be integrated into nanotechnology research and development (Fisher & Mahajan, 2006, p. 5).

In the first sentence, they admit to a global influence (“international funding race”) that leads to a highly nationalistic response (“aggressive US approach”). But even more interesting, in the second sentence Fisher and Mahajan admit to U.S. interests and efforts to solve the “public concerns” only at the national level through “legislative language requiring research on societal concerns.” The aggressive, nationalistic approach they report simply follows the tenor of the National Nanotechnology Initiative (NNI) set by Assistant to the President for Science & Technology and Director of the Office of Science and Technology Policy (OSTP) John Holdren. In his cover letter to the NNI Strategic Plan, Holdren outlines the goals of the NNI to include “transfer of nanotechnology into commercial applications *to benefit the Nation’s economy and the American people*” (Holdren, 2011, emphasis added). Despite somewhat less attention to “societal concerns” in Holdren’s language, they are very real, but a state can only reach within its own boundaries to resolve these.

Still, the U.S. government is seeking to pursue the concerns *sooner* rather than later (and the NNI *does* engage multilateral dialog through the Global Issues in Nanotechnology Working Group, see *nano.gov/gin*), and based on their summary, the trend is good. Fisher and Mahajan outline a fairly consistent involvement in this regard:

> Early consideration of the ethical and societal implications of nanotechnology would represent a departure from such traditional frameworks.... The NSF had sponsored a national conference in 2000 and a subsequent report in 2001 on the societal implications of nanotechnology. Also, it had funded multiple research and educational projects related to the subject. Furthermore, in April of 2003, the US Congress [House Committee on Science] held a public hearing on the societal implications of nanotechnology, in part to answer how “research and debate on societal and ethical concerns” can be “integrated into the research and development process” (Fisher & Mahajan, 2006, p. 9).

The indications are that the U.S. government is modeling transparent governance with emerging nanotechnology—at least to the extent we can monitor. Though this may come as no surprise, it should be equally unsurprising that this not necessarily the case with all nation-state governments. So while transparent governance is demanded by Allenby, and indeed is a luxurious backdrop enjoyed in the U.S. and other nation-states, it is not something that should be assumed.

Multicultural Dialogue

Multiculturalism and dialogue (Allenby, 2012).

Literature in multiculturalism abounds, but it is not something covered at great length or with any specificity in the governance literature. Accomplishing this might simply require a broader acknowledgement of the need for more focus on international cooperation in governance of emerging technologies (see introduction and discussion of *Transparent Governance*). But the lack might also exist because it is easy to conflate the concepts of multiculturalism and public values. This error must be avoided (see discussions of *Multi-dimensional Dialogue*). Undoubtedly, different cultures will engender different value systems (Haidt, 2007). But in most cases, while deeply held and sometimes shared, values are an individual expression of a complex back-story that has grown out of a specific cultural milieu that impacts many, not just one. It is this root, the broader back-story, about which this principle speaks. Allenby suggests that multicultural dialogue "can now be understood not as a luxury or an unfortunate necessity, but as a positive *value* for the future: it is an important source of growth" (Allenby, 2012). Note that not only is multicultural dialogue a value, but it is also a tool. That is, as "an important source of growth," it is clear Allenby views multiculturalism as a vital contributor to the solution space. Divergent ideas matter in the discourse, and distinctive cultural elements must be mined for their potential use in problem management. There is no better place to glean divergent ideas than from a different culture.

And culture itself is co-produced, reflecting the ebb and flow of the values it induces. The presence of such an odd feedback loop is among the reasons culture is complex. Haidt (2007) encourages us about the good such changes can bring, but at the same time we are reminded of its fragility:

> And because morality may be as much a product of cultural evolution as genetic evolution, it can change substantially in a generation or two. For example, as technological advances make us more aware of the fate of people in faraway lands, our concerns expand and we increasingly want peace, decency, and cooperation to prevail in other groups, and in the human group as well (p. 1001).

As a result, this is an important topic for governance.

While Jasonoff (2003) includes "distribution" due to globalization as one of the focal points in her technologies of humility, her exploration really only extends to the socio-economic differences within the community of the governed. While socio-economic differences can sometimes imply different cultural backgrounds, it is not a unique mapping. Still, trends are important and should be tracked (see *Quantitative Metrics*).

Roco seems to be the governance scholar most worried about internationalism, diverse backgrounds, and multiculturalism. For his part, he recognizes "cultural, political, and ideological influences" in both the scientific and government literature on emerging technology. He also reminds us that moral norms are not standardized and ratified at a global level, noting instead that "positions taken by various organizations have different flavors" (Roco, 2006, p. 14). This serves to remind us that there are many cultural milieus, and it is the knowledge encapsulated within these unique cultures that we wish to exploit in addressing our complex governance issues. Allenby suggests that mining diverse cultural heritage might uncover tools that can be used in managing complexity.

It behooves the governance scholars to consider multiculturalism specifically and more deeply than is currently done in the literature. This could possibly go along with a more thorough look at international cooperation (as outlined in the introduction).

A Part of the System

ESEM governance models must be flexible and able to respond quickly and effectively to changes in a system's state and dynamics; this will require including the policy maker as part of an evolving ESEM system, rather than as an agent outside the system guiding or defining it (Allenby, 2005).

In complex systems, the actors and designers are also part of the system they are purporting to design, creating a reflexivity that makes the system highly unpredictable and perhaps more unstable (Allenby, 2007).

Stoker (1998) suggests “governance refers to a complex set of institutions and actors that are drawn from but also beyond government” (p. 19). This is a start at acknowledging what this ESEM principle suggests. Stoker’s nod toward complexity is good (though it is likely that “complicated” is closer to what he had in mind). The fact that in his definition governance *subsumes* government and includes other non-government institutions is a step toward implying that we are, in fact, part of this complex system we are impacting. But this still doesn’t amount to a full acknowledgement of the reciprocal and (indeed) recursive relationship between governance and governed envisioned by Allenby.

Collingridge (1980) comes closer to anticipating this ESEM principle when he applies his “dilemma of control” to emerging technologies. In speaking of technology, he says “during its early stages, when it can be controlled, not enough can be known about its harmful social consequences to warrant controlling its development; but by the time these consequences are apparent, control has become costly and slow” (p. 19). This truism might trivially suggest we seek to govern emerging technologies between “early” and when “consequences are apparent,” but obviously further definitional work would be required. Less superficially, it can be observed that Collingridge is suggesting that governance of emerging technologies is extended and embedded. Unless there is active monitoring and engagement during the development phases, it is difficult to know where course corrections might be required. Anticipatory governance scholars Fisher and Guston (2011) have taken this seriously and are actively pursuing efforts to embed social scientists in technology incubation projects. Their Socio-Technical integration Research (STIR) initiative is the first of its kind and is intended to make technologists more reflexive about the ethical and social dimensions of their innovation processes.

Roco (2006) suggests that governance “move away from the previous *government* approach” (emphasis added) which attempts to regulate behavior in “detailed and compartmentalized ways.” Instead, a “governance” approach should be pursued; one where parameters and boundaries are established and within which “self-regulation” occurs (p. 3). It seems that only through this self-regulation—when participants in governance see themselves as a part of the wicked-complexity they are governing—that desired outcomes can be achieved. Of course, this leaves a huge problem of cross-cultural and international governance and seems to suggest that Roco’s idea of self-regulation may only work in fairly closed cultural spaces since self-regulation will be greatly influenced by cultural norms and values (see *Multicultural Dialogue*).

Rhodes (1996) scrapes closest to Allenby’s principle in allowing for governance to be emergent. He defines governance as “self-organizing, inter-organizational networks” (p. 66) which places him in support of Allenby’s dictum—though indirectly. By extension, if policy makers are part of these networks, then they are, of course, part of the system they are governing. Quoting Kooiman, Rhodes agrees that “no single actor, public or private, has all knowledge and information required to solve complex, dynamic and diversified problems.” This seems to leave decision-making to social structures “backed by no formal authority” and, in the words of Rosenau, only “by shared goals” (Rhodes, 1996, p. 657). Rhodes seems to envision a system in which formal governance is drawn out of the system’s actors, noticed belatedly, and recognized to be a network of influences driven by an invisible hand in a Smithian governance marketplace. This is a fairly serviceable definition of emergent behavior of exactly the sort to qualify as considering the policy maker as part of the system being governed. While not specifically answering the question of how we must govern, at least the participants in governance are now considered a part of the system itself; a part of the problem—and hopefully, a part of the solution.

The introduction alluded to the manner in which the governance literature is establishing a framework for managing both emerging technologies *and itself* as a discipline. In this context, such a reflexive posture can be thought to satisfy Allenby’s principle of being part of the system.

These activities are most evident in the work being done at the Center for Nanotechnology and Society at Arizona State University (CNS-ASU) in the area of *Anticipatory Governance* (Barben et al., 2008; Karinen & Guston, 2010). While still evolving, this framework for governance contains many tools for the assessment of technology and provides a framework for the application of these tools. As has already been stated, Anticipatory Governance has three pillars: foresight, engagement, and integration. *Foresight* employs tools like scenario development (cf. Rip & te Kulve, 2008) to help policy makers (indeed, all participants in governance) plan for the future. *Engagement* involves the public in governance using a variety of techniques including extended public forums (cf. Cobb, 2011). *Integration* inserts social scientists into laboratories to observe and potentially increase the reflexivity of the research scientists as they perform their regular research duties (cf. Fisher, 2007). Such programs are doing important work and have started to show some successes (Fisher, 2011). Treating governance as a complex system itself is an important step in making it what it needs to be in order to impact emerging technologies.

Systems *and* Artifacts

We must learn to engineer and manage complex systems, not just artifacts (Allenby, 2007).

In recognition of the lack of formalization in the field of complexity, Allenby expresses this more as a goal than as a principle. In fact, the literature on engineering and managing *complex adaptive systems* has been expanding for several decades and opinions still vary about what they are and how they are to be understood (see Mitchell, 2009 for an overview). Here, Allenby extends the notion of the previous principle by reminding us that technological artifacts—even those we consider simple—must never be considered as standalone entities but should be observed to have broader impacts. Each technological innovation will cause ripple effects that extend well beyond its immediate utility. Allenby has developed a simple framework for assisting in assessment and scenario development for emerging technologies and their artifacts (cf. Allenby, 2012, p. 164ff). The three levels of expanding impact are summarized and exemplified in Table 1.

Table 1. Technology Impact Levels

Level	**Impact**	**Example** (cf. Allenby, 2012, p. 165)
1	Immediate utility	Airplane provides rapid point-to-point transportation
2	Network, constellation, and cluster	Airplane leads to global air transport networks, scheduling systems, traffic impacts, business opportunities, etc.
3	Earth system	Airplane leads to leisure travel, impacts previously unreachable ecosystems, provides disease vectors, introduces UAVs, etc.

In general, it could be argued that because the literature pursuing better ways to govern emerging technologies exists at all, it demonstrates recognition of the need to understand and manage technology in a complex world. As such this acknowledges Allenby's principle. Still, there must be deeper and more thorough investigation into the ripple effects of technologies if we are to appropriately manage their trajectories. There is a start at this with the scenario development efforts that are coming out of the Anticipatory Governance *foresight* area (Selin & Hudson, 2010).

Continuous Learning

Ensure continuous learning (Allenby, 2007).

With this principle, Allenby is certainly implying that an ESEM practitioner should ensure that organizations involved in complex systems analysis display the characteristics of Senge's (1994) learning organization. As Senge describes it, team learning has three critical dimensions:

> First there is the need to think insightfully about complex issues... Second there is the need for innovative, coordinated action... Third, there is the role of team members on other teams (Senge, 1994, p. 236).

Senge's third dimension is about cross-pollination among teams—which is an important feature of this paper as it attempts to tie the governance literature to the sustainable engineering literature. But Allenby would also agree that learning must extend beyond people and teams. The entire complex socio-ecological system—parts and wholes (see *Systems and Artifacts* and *A Part of the System*)—must be established in such a way as to continuously learn. But, how can a system learn? Recall, complex systems learn all the time, though the terms generally used are "adapt" and "evolve." Creation of the necessary feedback loops and evaluative tools is a new and interesting area of research. This research is enabled by advances in information and communication technology as "big data" and modeling and simulation makes much more analysis possible.

Steve Rayner (2004) provides important insight in speaking of institutional learning "as a social construction" and about "the extent to which individuals rely on institutions to think and learn for them" (p. 351). His concept of institutional learning is "shared public knowledge in everyday use." To compare this shared knowledge to Allenby's interest in continual learning, it would have to include far more than that which is in “everyday use,” though that is a good start. Employing a biological analogy to the evolving complex system, we are reminded that the more frequent the use (think of a reproductive cycle), the more rapid the evolution. And it is this evolution which constitutes and reifies learning.

In some ways, Rayner’s “shared public knowledge” is reflected the Public Understanding of Science (PUS), which he finds hampered by untoward focus on the several “deficit models” that have been constructed around it. He outlines three deficits (knowledge of science facts, knowledge of science processes, and trust in scientists) that boil down to what he summarizes as a *communication* deficit (Rayner, 2004). Once again, the biological analogy serves us well because it is that “communication deficit” that prevents the spread of the meme (Dawkins, 1976; Blackmore, 1999) which prevents what Allenby wants: continuous learning (see also, *Real-world Boundaries*). But Rayner cautions:

> Framing the relationship between science and governance primarily as a problem of science communication domesticates it as a process problem that can be solved by the application of better communication techniques. It enables the institutions of science and governance to elide more fundamental structural challenges to established patterns of institutional authority in both science and politics. If the issue is one of communication, there is no need to question the appropriateness of existing procedures, established patterns of access to decision making, institutional prerogatives and power distributions (Rayner, 2004, p. 352).

In essence, he is saying that boiling the problem down to the need for “better communication techniques” is an oversimplification of the problem that hides the wicked-complexity of the system. It is not just about communicating better. It is about coming to terms with the real issues and ensuring continuous learning as they are resolved. Allenby would agree.

Jasonoff (2003) lists learning as one of the four focal points around which technologies of humility are constructed. This is important because when all admit to being learners, none will exhibit the hubris that comes when we smugly feel like we have achieved mastery. As Allenby would remind us, no one who admits to the complexity of a system can reasonably call himself its master (see *Targeted Intervention* and *No Explicit Control*).

Long-term Investment

Ensure that adequate resources, over time, are available for support of both the project and the associated science and technology research and development (Allenby, 2007).

Because “governing without government” (Rhodes, 1996) is still being defined (i.e., *emerging*), government policy and regulation are still primary drivers in the governance of emerging technologies. This current feature of governance fairly guarantees that the ESEM principle of long term investment is observed. It, however, must continue as an area of ongoing research as governance becomes more solidly defined—especially if “government” ultimately takes a lesser role in governance. Because as “government” wanes, so does its funding and concomitant ability to influence.

Fisher and Mahajan (2006) have already alerted us to the involvement of government in governance (see *Transparent Governance*), but also comment on the long-term investment principle as well. Noting that the “international pursuit of nanotechnology had become decidedly pronounced during the five-year period preceding the passage of the 21st Century Nanotechnology Research and Development Act” and reminding us of National Science Foundation (NSF) estimates “that the nanotechnology market would have an economic impact of over US$1 trillion by the year 2015” they point out that U.S. R&D investment in nanotechnology has increased from $116M in 1997 to $970M in 2004 (Fisher & Mahajan, 2006, p. 7). That is an indicator of long-term commitment that is required by Allenby’s principle. But the U.S. government has long been a steady supporter of emerging technology as exemplified by *nano.gov* which indicates total U.S. investment in nanotechnology to date of over $16B. And according to the trends shown by Sarewitz (2003, 2007), this can be counted on to continue, thus providing for adequate resources to support ongoing technology research and development.

Still, acknowledging a current funding situation does not make it permanent. If Rhodes’ emerging governance occurs, the implication is that the funding sources will be evolving as well, and hence, will not be guaranteed. As I alluded earlier, if funding for R&D comes with the promise of considerable return on investment, the public interest may cease to be served as profits begin to dominate the decision-making landscape. Provisioning of long term investment and what that means to governance is something the governance literature must take more seriously and address more directly.

Quantitative Metrics

Establish quantitative metrics by which progress can be tracked (for negative systems behavior as well) (Allenby, 2005).

While this could be considered neoclassical thinking in an age of alternative development theories (Martinussen, 1997), it is important to remember that measurement is vital or progress is difficult to assess (Roberts, 2010). In the governance literature, measurement seems to be restricted to some very limited surveys of public opinion and their attendant statistical analysis (Scheufele et al., 2007; Lee et al., 2005), or to presentations of public funding trends (Sarewitz, 2003, 2007). The majority of the literature seems to be focused on defining governance and its many models, analogies, and metaphors. Very little is said about how progress will be measured or even how success of governance might be judged.

In this regard, governance scholars can learn a lot from the efforts of the Stiglitz commission. In their *Report by the Commission on the Measurement of Economic Performance and Social Progress* (see *Mis-measuring Our Lives*, Stiglitz et al., 2010), the Stiglitz Commission upholds the value of the economic measures, arguing that, after all, many indicators of a country's well-being *are* economic, but outlines *three axes* of progress that provide a very balanced view of overall well-being: *economic and monetary*, *quality of life*, and *sustainability/future*. The *economic measures* are the traditional metrics associated with the neoclassical approach. The inclusion of the *quality of life measures* is a nod toward the capabilities approach for human development (Nussbaum & Sen, 1993; Nussbaum, 1998; Roberts, 2010) espoused by the United Nations Development Programme (UNDP). But now, not only are these listed as equals with the economic measures, they are given increasing importance in the overall suite of measures. The inclusion of *sustainability metrics* is unprecedented and, while such metrics are still in planning, these represent a very encouraging step. The report advocates a "shift of emphasis from a production-oriented measurement system to one focused on the well-being of current and future generations, i.e., *toward broader measures of social progress*" (Stiglitz et al., 2010, p. 7, emphasis added). Indeed, throughout the report this becomes an oft-repeated mantra indicating a drive to "shift emphasis from measuring economic production to measuring people's well-being. And measures of well-being should be put in the context of sustainability" (Stiglitz et al., 2010, p. 10).

The Stiglitz Commission is able to leverage much prior art in this regard and defines quality of life as "the full range of factors that make life worth living, including those that are not traded in markets and not captured by monetary measures" (Stiglitz et al., 2010, p. 92). If development is about human flourishing, then we must track the quality of life indicators, both subjective and objective. The implications are that governance scholars can leverage the Stiglitz Commission's three-axis model and can begin to measure and track the public values they are monitoring.

This must become a much deeper area of governance research. For example, how will Rhodes (1996) measure his governance networks? Recall that both their development and their effectiveness in governance must be measured.

No Explicit Control

Unlike simple systems, complex, adaptive systems cannot be centrally or explicitly controlled (Allenby, 2007).

In this principle Allenby recites the "dilemma of control" for complexity theory. Collingridge notes a similar dilemma of control for emerging technologies:

> Attempting to control a technology is difficult, and not rarely impossible, because during its early stages, when it can be controlled, not enough can be known about its harmful social consequences to warrant controlling its development; but by the time these consequence are apparent, control has become costly and slow (Collingridge, 1980, p. 19).

It is because of the reality of this dilemma that frameworks like ESEM and anticipatory governance exist. The hope is that *foresight*, whether implemented as technology roadmapping, scenario development, life cycle assessment, or any of a host of other available tools, can better prepare technologists and policy makers for the uncertainties that lie ahead. The outcomes of *engagement* exercises can provide understanding of the kind of world in which the public wants to live and ensures informed consent of the governed. The impact of *integration* can compel a researcher to think through ramifications of research (whether ethical, legal, or social) while it is ongoing and adjust accordingly. While none of these can individually or in combination ever presume to control the emergence of a technology, they can at least combine to help us be prepared for the future. The existence of anticipatory governance literature implies there is some belief that the future is in some way manageable if not controllable. This is the hope of all good planning. Perhaps the role of such governance is simply to pave the way with useful alternatives or contingencies. There certainly must be a balance between a fatalistic technological determinism and an arrogant presumptiveness that leads to a feeling of control where none exists. This leads us directly to the next principle.

Expect Emergence

In complex systems, emergent characteristics occur at high levels of system organization, so evaluations of scale are vital. Scale-up should allow for inevitable discontinuities and emergent characteristics (Allenby, 2005).

With this principle, Allenby simply is expressing the inability to understand and project the future of complex systems. The nuance added is that such systems will grow, and change, and evolve new characteristics. He suggests that as systems grow in size and complexity, sufficient planning must occur to allow for those inevitable discontinuities. While this sounds like a simple repetition of the previous principle ("You can't control complex systems."), it is actually a much more powerful statement: "No, really, you can't!"

While admitting to a lack of explicit control over technological trajectories, Fisher, Mahajan & Mitcham (2006) suggest there is a significant amount of "midstream modulation" that can occur as the researchers respond reflexively to the "upstream agenda setting" and the "downstream regulation, market selection, and use" (p. 491). Like most changes in plans, however, avenues for such midstream modulation generally must have been prepared in advance:

> However, a central challenge to midstream modulation is preparing the ground for the effective application of modulation strategies. To a significant extent, modulation capacities would need to be conceptualized and developed locally and from the bottom up to ensure that methods are neither unproductive, tedious, nor counterproductive—or are seen to be so (Fisher, Mahajan & Mitcham, 2006, p. 492).

Whether "preparing the ground" means (metaphorically) incorporating highway inspection stations where the heat of the brakes can be checked, or whether it means building run-away truck ramps that can be used when "midstream modulation" is required, *it is work that must be done in advance, in anticipation of midstream modulation*. Such efforts are generally included as an element of good planning. As such it is another admission that control is not an available alternative, and that we must plan well enough to afford ourselves some options when things go differently than expected (or horribly wrong).

An admission of the possibility of "emergence" seems to fly in the face of anticipatory governance. Governance can only provide a landscape on which outcomes play. It can do nothing to write a script for the drama. In order to establish the landscape and ground rules, a governed public must decide on the future it desires and ensure that developments occur only in the direction they allow. While challenging, this is not an entirely wistful longing. There has been progress, for example, in the area of nuclear arms reduction and disarmament. While nuclear war still looms as an imminent threat in the 21st Century, it is somehow *less* imminent than it was in the 20th Century during the Cold War. The threat may never be eliminated, but governed publics have gone on record about their interest in working toward that end. Similar broad brush claims can be made, for example, about progress in reducing toxins from children's toys, keeping aquifers safe from contamination, and developing "green" energy sources. While nothing is guaranteed, the landscape is being suitably groomed for progress in the direction of public interest.

Within complex earth systems, however, technology is and has always been a wildcard. Hence, it is impossible to completely preclude emergent characteristics that will ultimately interfere with best laid plans.

Incremental and Reversible

Policy, design, and engineering initiatives should be incremental and reversible, rather than fundamental and irreversible (Allenby, 2005).

Premature lock-in of system components should be avoided where possible. Whenever possible, engineered changes should be incremental and reversible, rather than fundamental and irreversible (Allenby, 2012).

As a sort of precautionary principle, Rittel and Webber (1973) speak of "the art of not knowing too early which type of solution to apply" (p. 164). The warning is relevant since too frequently, alterations which are not well thought-out will lead to lock-in that disallows switching back to former status quo. The idea of incremental and reversible changes should evoke the idea of "tweaking" the system—making adjustments that can easily be unmade in the sense proposed by Sarewitz and Nelson (2008, see *Evaluate Technological Fix*). Such incremental adjustments are not "shots in the dark" but carefully analyzed and planned. They are appropriate implementations of the scientific method. They are also examples of adaptive management.

Though there are certainly instances of policy and law changes that exemplify this principle (e.g., laws limiting maximum highway speed in the U.S. to 55 mph were later abandoned and reverted to 75 mph), it seems that the governance literature takes this kind of adaptive management for granted. That is, there is not trend of suggestions for small adjustments that can be monitored and measured over multi-year periods to see if empirical evidence can be gathered to support policy changes. To date, there is insufficient water under the "new governance" (Rhodes, 1996) bridge for there to be credible examples in the literature of successful incremental changes to either governance itself or the technologies governed. Neither have there been studies to document incremental changes that were measured to be *ineffective* (see *Quantitative Metrics*) and consequently reversed in order to restore the system to its previous status quo. Even the recent example of changes in controls on STEM cell research in the U.S. (i.e., differences in the policies of the Bush and Obama administrations) seem to be more about political expedience than smart technology management. While the governance literature is not yet there, they certainly hope to be soon.

Once again, Collingridge appears to be prescient on the matter and can be called on to summarize:

> The essence of controlling technology is not in forecasting its social consequences, but in retaining the ability to change a technology, even when it is fully developed and diffused, so that any unwanted social consequences it may prove to have can be eliminated or ameliorated (Collingridge, 1980, p. 20).

Designing such an "undo" button has proven to be difficult, but it is something that ESEM principles demand.

Resilient not *simply* Redundant

Aim for resiliency, not just redundancy, in design (Allenby, 2007).

Many critical systems have built-in redundancy so if a primary system suffers a catastrophic failure, the backup system can take over operations. According to Allenby, *resilient* systems resist degradation in performance and when they must degrade, they do so gracefully (Allenby, 2012, p. 370).

The governance literature does not speak of resilience though it must start to do this. An important place to start might be in reference to the items mentioned in the introduction. Specifically, in the face of an international push to develop an emerging technology (e.g., nanotechnology or STEM cell research), we must ask if our governance structures and political will are strong enough to manage dissent and defection (*sensu* Callon, 1986) in the event of extreme public polarization. Note well that defection means the defectors are no longer under the control of the regime from which they defected. Since what they do *there*, impacts us *here*, we must ask if we are resilient enough to manage it.

A fitting way to end our pass through the ESEM principles is to be reminded once again of Sheila Jasonoff's technologies of humility. One of her focal points is a word closely akin to resilience: vulnerability (Jasonoff, 2003, p. 241). In Jasonoff's context, vulnerability refers to those individuals and groups that are vulnerable in a socio-economic sense. Since the ESEM principle of resilience spans all domains, this is not an invalid mapping. Any vulnerability is a design space for resilience. Further, it sometimes helps us to remember that people, our public, are at the same time the most vulnerable and the most resilient parts of our governance system. It behooves us to deal well with our public.

Conclusion

This brief walk through the ESEM principles and abbreviated survey of the governance literature has demonstrated that they exhibit many similarities in vernacular and approach to managing the complexity of governance. But, as might be expected given its engineering roots, this survey has also clearly demonstrated that ESEM suggests a far more empirical approach to such governance. Further research is required to fill in any blanks and also demonstrate domains of discourse into which governance delves that ESEM does not address. The appendix serves to outline the gaps.

It is important to notice, however, that both the governance literature and Allenby's ESEM principles acknowledge the involvement of people as primary contributors to the complexity that is to be managed. It is axiomatic that if a simple system can be found one need only add people to turn it into a complex one. With people comes wicked complexity. While ESEM stresses inclusion of the human dimension in analysis, it freely admits to the difficulties in establishing and collecting quantitative metrics.

Writing in response to Rittel and Webber (1973), Rosenhead (1996) outlined his approach for dealing with complex social planning problems of the wicked sort. Rosenhead's approach is summarized nicely by Tom Ritchey (2005, emphasis added):

- Accommodate multiple alternative *perspectives* rather than prescribe single solutions
- Function through *group interaction* and iteration rather than back office calculations
- Generate ownership of the problem formulation through *stakeholder participation* and *transparency*
- Facilitate a graphical (visual) representation of the problem space for the systematic, *group exploration* of a solution space
- Focus on *relationships* between discrete alternatives rather than continuous variables
- Concentrate on *possibility* rather than probability.

Many of these words, phrases, and concepts are strikingly reminiscent of the *anticipatory governance* literature. Key words fly from the list when the three pillars of *foresight*, *engagement*, and *integration* are rehearsed and ruminated upon. Also unsurprising is their similarity to the ESEM literature. Both frameworks admit to wicked-complexity—ESEM directly, anticipatory governance indirectly. Hence, both frameworks have made an effective first step in governance.

In closing, it is important to observe that when words like "perspectives," "group," "participation," and "transparency" are used, it is clearly the language of dialogue. Managing complexity, especially wicked-complexity involves conversation. It is in conversation that understanding comes. It is in conversation that we hear people's stories—and stories can be fun. But stories take time, and understanding takes time, so "governance practitioners" must not allow themselves to fall prey to the extortion that they are falling behind; that they must, as the old proverb says, "sacrifice the important on the altar of the urgent." Governance must assume the perspective espoused by the ESEM principles: dialectic *and* quantitative; acknowledging and embracing the power of technology while refusing to succumb to the siren call of the technological fix.

Appendix: ESEM as Governance Summary

ESEM Principle	Coverage in Anticipatory Governance Framework	Coverage in Governance Literature at Large	Relevant Sources
Targeted Intervention	Foresight	Yes	Roco 2006; Barben et al. 2008
Evaluate Technological Fix		Weak	Douthwaite 1983; Rosner 2004; Sarewitz & Nelson 2008
Real-World Boundaries	Foresight, Engagement, Integration (with opportunity)	Yes	Cash et al. 2003; Pielke 2007; Stoker 1998; Rayner 2004; Guston 2000; Barben et al. 2008; Jasonoff 1987
Multi-dimensional Dialogue	Engagement	Yes	Barben et al. 2008; Cobb 2011; Bozeman & Sarewitz 2005; Macnaghten et al. 2005; Jasonoff 2003, 2007; Pielke 2007
Techno-Social Differentiation		Weak	Collingridge 1980
Transparent Governance		Weak (assumes democracy)	Rhodes 1996; Roco 2006; Jasonoff 2003; Fisher & Mahajan 2006
Multicultural Dialogue		Weak	Jasonoff 2003; Roco 2006
A Part of the Problem	Foresight, Engagement, Integration	Yes	Collingridge 1980; Rhodes 1996; Stoker 1998; Roco 2006; Barben et al. 2008; Karinen & Guston 2010; Rip & te Kulve 2008; Cobb 2011; Fisher 2007; Fisher 2011
Systems *and* Artifacts	Foresight	Weak	Barben et al. 2008
Continuous Learning		Weak	Rayner 2004; Jasonoff 2003
Long-term Investment		Weak (assumes public funding)	Fisher & Mahajan 2006; Sarewitz 2003, 2007
Quantitative Metrics		Weak (post hoc analysis and PVM)	Scheufele et al. 2007; Lee et al. 2005
No Explicit Control		No	Collingridge 1980
Expect Emergence		No	Fisher, Mahajan & Mitcham 2006
Incremental and Reversible		No	Collingridge 1980
Resilient not *simply* Redundant		No	Jasonoff 2003

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