J Agric Environ Ethics (2012) 25:467–484
DOI 10.1007/s10806-011-9342-2

ARTICLES

Sustainable Engineering Science for Resolving Wicked Problems

Thomas Seager · Evan Selinger · Arnim Wiek

Accepted: 3 September 2011 / Published online: 15 September 2011

Abstract Because wicked problems are beyond the scope of normal, industrial-age engineering science, sustainability problems will require reform of current engineering science and technology practices. We assert that, while pluralism concerning use of the term sustainability is likely to persist, universities should continue to cultivate research and education programs specifically devoted to *sustainable engineering science*, an enterprise that is formally demarcated from business-as-usual and systems optimization approaches. Advancing sustainable engineering science requires a shift in orientation away from reductionism and intellectual specialization towards integrative approaches to science, education, and technology that: (1) draw upon an ethical awareness that extends beyond the usual bounds of professional ethics or responsible conduct of research to include *macroethics*, (2) adopt anticipatory and adaptive approaches to unintended consequences resulting from technological innovation that result in more *resilient* systems, and (3) cultivate *interactional expertise* to facilitate cross-disciplinary exchange. Unfortunately, existing education and research training programs are ill-equipped to prepare scientists and engineers to operate effectively in a wicked problems milieu. Therefore, it is essential to create new programs of graduate education that will train scientists and engineers to become sustainable engineering science experts equipped to recognize and grapple with the macro-ethical, adaptive,

---

T. Seager
School of Sustainability and The Built Environment, Arizona State University, Phoenix
Metropolitan Area, AZ, USA
e-mail: Thomas.Seager@asu.edu

E. Selinger (✉)
Department of Philosophy, Rochester Institute of Technology, Henrietta, NY, USA
e-mail: evan.selinger@rit.edu

A. Wiek
School of Sustainability, Arizona State University, Phoenix Metropolitan Area, AZ, USA
e-mail: Arnim.Wiek@asu.edu

and cross-disciplinary challenges embedded in their technical research and development programs.

Keywords Sustainability · Sustainability ethics · Wicked problems · Interactional expertise · Resilience · Macro ethics

Introduction

Sustainability problems are widely recognized as wicked problems (Norton 2005; Raffaelle et al. 2010; Brundiers and Wiek 2010). Questions, however, remain as to what this designation actually means and what institutional changes should accompany the understanding expressed by this unusual characterization.[1] The wickedness of sustainability is especially challenging, as core issues entail complexity irreducible to industrial-age, technological challenges. In both formal and informal settings, we regularly have observed engineering and science scholars expressing conflicting views that range from conservative to proactive with regard to the need for reform in science, engineering, and technology research and education.

The more conservative view suggests that the culture guiding scientific research does not need to change fundamentally to advance sustainability. From this perspective, science can meet the challenges of sustainability by inventing sustainable technologies that drive innovation. Efficiency gains, carefully bounded problem-solving within specialty fields, as well as risk management and systems optimization are the guiding ideals. For these adherents, optimism exists that science's ethical, educational, and procedural cultures do not require significant transformation. Simply put, this outlook suggests that any aspects of complexity unaddressed through innovation fall outside the bounds of "normal" science (e.g., Funtowicz and Ravetz 1993), which we characterize as *business-as-usual* and *systems engineering*.

A more proactive view suggests that some scientific sectors require a radical reorientation in order to meet the challenges imposed by sustainability problems. From this perspective, technology development needs to be framed and explored in ways that differ fundamentally from standard practice, and ultimately effect normative, strategic, behavioral and other changes in society. Although not *activist* in a political sense, adherents of this view advocate for the recursive goal of continuous improvement and adaptation via technology, policy, and social experiments conducted in real and complex settings. In terms of the *Sustainability Spectrum* (Seager 2008), the conservative view is associated with longevity and reliability, while the proactive view is more closely associated with resilience and renewal. We associate *sustainable engineering science* with this more proactive view.

Our main aim in this paper is to strengthen understanding of sustainable engineering science by showing how it is differentiated from business-as-usual and

---

[1] With permission of Vincent Hendricks, this paper is a revised version of ideas expressed earlier in Thomas Seager and Evan Selinger's "The Incompatibility of Industrial Age Expertise and Sustainability Science" in *Expertise: Philosophical Reflections* (Automatic/VIP Press: 2011), pp. 99–118.

systems engineering. Even while acknowledging that conservative approaches do make essential contributions to sustainability, we argue that only sustainable engineering science contains the features necessary to resolve wicked problems. Although we will explain the logic of business-as-usual and systems engineering approaches, and provide examples that support our claims, our analysis of sustainable engineering science will be restricted to conceptual discussion and illustrative examples of its essential characteristics.

The paper is organized in several parts. First, we call attention to the identification of wicked problems as a *critique of industrial-age science* that applies to sustainability. Then, we present a comparative taxonomy of the three different approaches to sustainability in the context of science and technology, and provide a detailed description of the defining characteristics of sustainable engineering science. The remaining sections are organized around analysis of distinctive characteristics of wicked problems, including problem formulation and open-ended time frames, and clarification of how sustainable engineering science addresses these by: (1) making explicit the central role of macro-ethics (beyond professional or social ethics), (2) expanding risk-based design and management approaches to incorporate anticipatory, adaptive, and resilience-based considerations, and (3) describing the necessity of a change in understanding the role of and demands upon scientific expertise in relation to wicked problems.

Sustainability as a Wicked Problem

A fundamental conceptual connection between sustainability and wicked problems (Rittell and Webber 1973) is largely attributable to Norton (2005), who argues that sustainability problems typically exhibit ten characteristics (which, in principle, can be reduced to five) that are constitutive of wicked problems: difficulties in problem formulation, multiple but incompatible solutions, open-ended timeframes, novelty (or uniqueness), and competing value systems or objectives. However, similar concepts were developed earlier by Funtowicz and Ravetz (1993) and Dovers (1996). Despite Norton's compelling characterization, *scientific organizations rarely characterize sustainability in "wicked" terms*. While the Brundtland Commission (1987) report explicitly incorporates environmental, economic, and social concerns, it nevertheless interprets sustainability in narrow economic terms, as a problem of natural resource stewardship and equity of income distribution (Brundtland and Khalid 1987). This perspective cannot be absolute. Contexts exist in which sustainability requires understanding of complex global systems in which cause and effect relationships are extraordinarily difficult to decode, deliberation is encumbered by contrasting value judgments or cultural norms that are far from universal, and the relevant knowledge resides in multiple disciplines that lack streamlined techniques of collaboration. Moreover, because technological innovation will play an important role in enabling future generations to meet their own needs, debates over how to operationalize sustainable parameters remain tethered to divisive views regarding the relations between science, technology, and progress. For these and related reasons, sustainability is best understood as an *essentially* *contested concept* (Gallie 1956; Connolly 2007). Therefore, the logic of wicked problems moves expertise beyond the scope of the Brundtland Commission *because it calls to attention to the limits of normal scientific expertise*.

In other words, the Brundtland Commission, along with most university programs in sustainable science and engineering, mostly *gesture* to sustainability being a post-industrial concept, while in practice, their outlook expresses confidence in what we call the industrial-age science paradigm—i.e., the science that co-evolved in close concert with industry, and is guided by an ethos driven by manufacturing and production. While the advances in these areas of science and technology during the last 40 years have been extraordinary, it is not yet clear that they have contributed significantly to resolving complex problems of social progress. At the core, the concept of wicked problems points out that a theory of planning "ain't rocket science"—in fact, it's much harder. The obvious implication is that a *new type of scientific expertise is required for a post-industrial age*. Nonetheless, the scientific community, despite being quick to adopt the rhetoric of sustainability as a legitimate goal of science, has been slow to accept the critique of science on which a deeper understanding of sustainability reposes. As wicked problems are deeply nested in the current societal structures, a science that ventures to address such problems accepts or even seeks to get entangled with power, politics, and other "realities," which is a dangerous yet inevitable engagement (Talwar et al. 2011).

A Taxonomy of Sustainable Engineering Science

To clarify fundamental differences between understandings of sustainability that confront and ignore wicked problems, we offer here an idealized taxonomy that identifies three general approaches to sustainability: "business-as-usual," "systems engineering," and "sustainable engineering science" (Table 1). Although simplifying strategies are needed to construct this taxonomy, the taxonomy accurately captures our main point: *only sustainable engineering science*, *which is in the minority*, *is informed by an understanding of wicked problems*.

Business-As-Usual

The most common approach to sustainability is to simply repackage the normal incremental practice of research and development as pertaining to making the world in general a better place—and, as a consequence, relevant to sustainability. This approach is typically extraordinarily optimistic about the prospects of technology to improve the human condition. That is, it presupposes that the introduction of new capabilities will necessarily improve environmental, social, and economic quality. However, the business-as-usual approach typically ignores environmental and social issues altogether, especially those issues that may only emerge at scales, and may even ignore relevant economic considerations. Ultimately, the emphasis in science when conducted as usual is on creating knowledge that leads to new capabilities, regardless of broader contextual questions.

Table 1 Science and technology orientations towards sustainability

	Attitude towards technology	Focus	Expert and ethical culture	Approach to complexity	Approach to conflicting views
Business-as-usual	Optimism	Creating new things, resources. Ignores scale and efficiency	Depth in a single sub-discipline. Professional ethics	Simplification and reduction	Defense of techno-industrial ethos. Denial of opposing perspectives
Systems engineering					
Engineering within ecological constraints	Pragmatism	Cost optimization of maturing technology. Ignores scale	Compart-mentalized, multi-disciplinary teams. Social ethics	Cost-benefit optimization and efficiency	Litigation and regulation
Sustainable engineering		Optimization for triple bottom line. Ignores scale		Risk minimization	Structured participation
Sustainable engineering science	Skepticism	Sustainability as a wicked problem	Interactional expertise. Macro ethics	Anticipation, Adaptation and resilience	Cooperation and deliberation

For example, the discovery of carbon nanotubes (CNT) by Sumio Iijima (1991) set in motion a multi-billion dollar research and development effort directed towards characterization and engineering of CNT for applications in wiring, catalysis, structures, and electrochemistry. Far less effort has been expended in the area sustainability concerns, such as health and life-cycle environmental effects (Theis et al. 2011)—despite the fact that some CNT are currently more energy-intensive in manufacture than even the most high-tech materials, including crystalline silicon semiconductors (Healy et al. 2008), and may be hazardous under certain exposure scenarios (Oberdörster et al. 2005, 2007).

While the business-as-usual approach may lead to scientific breakthroughs in materials, medicine, energy systems, and other technologies that generally correlate with human progress, objectors claim it yields advances in technology that disproportionately benefit the rich and thereby exacerbate social inequality (Woodhouse and Sarewitz 2007). The usual response to this critique is two-pronged:

1. The scientific enterprise is capable of generating technologies appropriate for underprivileged classes or underdeveloped countries. Therefore, the fault lies not with science and technology *per se*, but their application and distribution; and,
2. The poorest people in industrialized countries today are far better off than typical, pre-industrial populations. Therefore, the *disparity* between rich and poor is not as important as the *absolute level* of well-being among the poorest.

A minority—but certainly not inconsequential—view is that the business-as-usual approach is morally problematic when it is driven by and reinforces consumerism. Borgman (1984) characterizes consumerism as a spectator's orientation to life that is fostered by the dominant modern technological trajectory called the "device paradigm"—a paradigm that putatively seduces people to passivity by addicting them to the artifacts of technology that separate means from ends and strip away meaning. Such addiction, Borgmann insists, undermines "focal" activities that are anchored in context and tradition, and that require skillful activity to yield memorable experiences where psychological "flow" abounds. As Aidan Davison (2001) notes, Borgmann's perspective suggests the business-as-usual approach can accommodate some sustainable ends even while remaining divorced from the virtue ethics goal of creating cultures that are guided by practices that provide genuine psycho-social-spiritual *sustenance*.

Systems Engineering

A more modern approach to sustainability involves what may generally be described as systems engineering. Two perspectives dominate this domain, both of which seek improvement at the scale of integrated systems, rather than piecemeal component optimization. The first outlook is *engineering within sustainability constraints*. In this approach, engineering systems are typically optimized for traditional objectives, such as cost minimization or rate of return maximization, but under more highly constrained conditions than have historically been the case. Environmental emissions standards—both regulatory compliance and voluntary standards that exceed compliance (such as L.E.E.D. certification for green buildings)—provide illustrative examples, as does the increased interest in stakeholder and public participation at early stages of engineering design development.

The second perspective goes even further than the first by expanding the design objectives themselves to incorporate the *triple bottom line* of sustainability: economy, environment, and society. In this approach, environmental quality and social objectives are not merely constraints to be met. They are understood as design objectives in their own right that ultimately necessitate assessment of trade-offs with respect to one another and cost. For example, the savings in fuel costs that result from hybrid automobiles may not justify the increased purchase price of the technology under all but exorbitant fuel price scenarios. Nevertheless, hybrid autos provide environmental benefits in the form of reduced tailpipe emissions—especially in congested urban areas that are most impacted by poor air quality. These benefits partially justify government programs that subsidize the private purchase of hybrid cars through tax credits (Keefe et al. 2008). More speculatively, the claim can be made that hybrid cars provide social benefits to the owners that perceive enhanced social standing in the community or derive satisfaction from a conspicuous display of environmental awareness, and that these social dimensions justify the increased expense. After all, it has long been a tradition in the auto industry to advertise cars based upon the importance drivers place on self-image. From a systems perspective, then, hybrid automobiles appear to exemplify technology that incorporates economic, environmental, and social considerations in design.

Nonetheless, engineering optimization within ecological constraints and the triple-bottom line approaches are almost universally an exercise in *marginal* analysis that ignores questions of scale, and are therefore vulnerable to the criticism that the new technologies that make goods more efficiently (and therefore cheaper) will result in unsustainable growth in consumption. In several cases, historical examples support this critique (e.g., *The Coal Question*, Jevons 1865) by showing that increases in consumption occur simultaneously with increases in efficiency. The typical rebuttal is that technological substitution has driven downwards the price of almost all basic commodities and manufactured goods throughout the Industrial Revolution (with the possible exception of lumber, Simon 1996). To the extent that price is an indicator of scarcity, long-term declining prices would seem indicative of *increasing* abundance, despite concurrent increases in consumption. However, this reasoning ignores several conditions that are not captured in market prices, including: external costs, *negative* prices, and instances in which historically unpriced public goods become scarce and costly (Ayres 1998). Moreover, for almost all sustainability problems, there are non-technical, social and behavioral solutions that are (sometimes) cheaper, better, and more sustainable than any technological solutions. Thus, careful reflection and deliberation on the role of technology is required for resolving sustainability problems (Sarewitz and Nelson 2008).

Sustainable Engineering Science

At the extreme, sustainable engineering science represents a paradigm shift in the way that science approaches problems of technology and complex systems. The term makes reference to concepts of science working at the boundaries of “industry and nature” (Clark and Dickson 2003), and that differentiate science that is “defined by the problems it addresses rather than by the disciplines it employs” (Clark 2007). We expand upon this understanding here by further describing the differences between sustainable engineering science and other approaches to science. In normal, industrial-age science, problems are defined narrowly and potential solutions circumscribed by that narrow definition. This involves assessing the relative merit of any particular technology as a matter of defining measureable performance objectives (e.g., dollar per watt installed capacity of photovoltaic systems, or central processing unit computational cycles per second) and defining success as achieving correlative policy or technology objectives (e.g., meeting Corporate Average Fuel Economy standards). The systems view described earlier introduces broader aspects of the problem such as may be suggested by a life-cycle perspective. However, in the domain of wicked problems, these approaches encounter several difficulties.

With regard to problem formulation, the evolving and recursive nature of wicked problems demands a constant cycle of anticipation and adaptation as new information about feedback effects and unintended consequences is discovered. While it can be said that science in a business-as-usual paradigm is responsive to these discoveries, the ethical orientation, disciplinary approach, and narrow focus of industrial-age science introduces obstacles and delays in that feedback that can exacerbate the unintended consequences of technological progress. For example, physicists and materials scientists developing CNT-based technologies typically lack the cross-disciplinary expertise necessary to understand toxicological and life-cycle environmental concerns. Similarly, toxicologists typically lack the specialized knowledge of nanomaterials required to fully characterize those properties of CNT that are germane to biological health responses or environmental fate. When considering sustainability concerns, the business-as-usual approach is significantly handicapped by the degree to which knowledge resides in increasingly narrow specializations (Wiek et al. 2007). Ultimately, technological progress under the business-as-usual paradigm could *exacerbate* wicked problems, rather than contribute to their resolution.

Systems engineering represents an improvement on business-as-usual in that it explicitly attempts to incorporate broader, contextual concerns. Nevertheless, it remains deficient in several respects that result primarily from the focus of systems engineering on efficiency. The natural maturation of any new technology typically involves an incremental evolution from focus on new techniques in the business-as-usual approach, to optimization of manufacturing or life-cycle considerations. Optimization requires an objective function that provides the basis for comparing the overall merit of different design alternatives. Selection of any one objective criterion necessarily excludes others. Consequently, an optimization approach requires advancing one normative view of technology at the expense of others. As any particular engineered systems expands in terms of *scale*, it must increasingly encounter constraints or other interactions with both other engineered systems that have been advanced under competing ideals, and complex, adaptive natural systems. Two points of irreconcilable conflict arise.

The first is the conflict between different idealized visions of the engineered system, such as might be encountered in the context of climate change. For example, legitimate, value-laden disagreements with regard to the optimal levels of carbon dioxide in the atmosphere inevitably lead to different visions of the optimal technology platforms on which energy systems should be based. Conflicts between different views can not be reconciled on the basis of technical performance standards alone, which relates directly to the characteristic of wicked problems that can be described as multiple or competing value systems.

The second point relates to complexity. Even if universal agreement could be attained on what constitutes the overall merit of any technological alternative, the resulting engineered system would (at scale) inevitably be subject to interactions with complex, adaptive natural and social systems. Emergent behaviors and properties of complex systems mean that any optimization of existing engineered systems is at best myopic (and at worst, exacerbating risk of catastrophic collapse). That is, conditions only *appear* optimal from the narrow perspective of the existing timeframe. For example, the widespread adoption of transgenic crops resistant to the herbicide glyphosate during the 1990s resulted in economic benefits in terms of increased yields, as well as environmental benefits resulting from lower herbicide volumes and tillage requirements. However, the recent emergence of glyphosate-resistant weed species in many regions of the United States has required a return to more traditional practices, such as crop-rotation, tilling, and intensive application of aggressive herbicides. In retrospect, the benefits of transgenic crop technologies could have been extended if they had been deployed at a more limited, albeit suboptimal, scale. Thus, what *appears* to be optimal from a reductionist perspective may nevertheless lead to suboptimal (or perverse) feedback effects with their genesis in complex systems.

Sustainable engineering science does not necessarily reject business-as-usual or systems engineering approaches as appropriate to problems that can be tamed (Sarewitz and Nelson 2008). In this respect, sustainable engineering science is *not fundamentalist*. Its practitioners should not conceive of themselves as advancing research in something like the one true form of authentic sustainability. However, sustainable engineering science is guided by recognition of the reasons why the two main alternatives fail when confronting wicked problems. Crucially, it proceeds with an understanding that many paths of technological development aspire for non-contested, business-as-usual, results, but fail to realize this ambition as a result of reaching levels of growth that engender deeply contested and surprising outcomes, some of which fall so short of motivating intentions as to be best characterized as perverse. When this happens, technologies originally developed under a business-as-usual paradigm tend to get recast in a systems engineering approach that attempts to minimize broader adverse impacts.

One example is chloro-fluorocarbons (CFCs). Originally discovered by Thomas Midgley, CFCs were hailed has safe (i.e., nonexplosive), energy efficient, and non-toxic alternatives to problematic refrigerants such as ammonia or propane. The widespread adoption of CFCs enabled development of inexpensive refrigeration and air-conditioning technologies, with concomitant benefits in food preservation and the rapid growth of urban centers such as Atlanta and Phoenix in the American South. However discovery of CFCs in the atmosphere by James Lovelock (Lovelock 1971; Lovelock et al. 1973) soon led Rowland and Molina (1975) to hypothesize that unchecked use of CFCs would eventually lead to catalytic destruction of the stratospheric ozone layer. The response of the techno-industrial complex at first was complete denial and attempts to discredit Rowland and Molina. Nonetheless, CFCs were soon afterwards nearly completely banned by the Montreal Protocol in 1987. Both Rowland and Molina (along with Paul Crutzen) were eventually awarded the Nobel Prize in Chemistry that eluded Midgley. Now, the substitutes for CFCs (hydrofluorocarbons, or HFCs) are themselves implicated as significant contributors to an even more complex problem—global warming (Seager and Theis 2003, 2004).

By contrast, sustainable engineering science responds to the recognition that industrial-age approaches to science have failed to successfully grapple with the wicked problems of modern technology. While we acknowledge that modern science has to its credit innumerable achievements, it can also be said that the myopia of modern science has left a legacy of complex social, environmental, and economic problems. In this context, sustainable engineering science represents a post-industrial attempt to change both the perspective and the approach to science that created complex problems (such as hazardous waste or climate change). Like other emerging fields, sustainable engineering science has been criticized as lacking defined boundaries or accepted investigative methods. Nevertheless, it is defined by a robust set of principles and concepts (Kates et al. 2001; Fiksel 2006; Komiyama and Takeuchi 2006; Michelcic et al. 2003; Wiek et al. 2011).

Our main argument, therefore, is that while technological approaches to sustainability can be understood as pluralistic and evolve from one paradigm to another, sustainable engineering science represents at least three major departures from other approaches: (1) it is predicated upon an understanding of the macro-ethical requirements of technology development as extending beyond merely research or professional ethics; (2) it deliberately migrates from risk-based systems optimization to anticipatory and systems resilience perspectives (e.g., Korhonen and Seager 2008); (3) it proceeds with an awareness of the necessity of consciously cultivating the interactional expertise necessary to carry out integrative (compared with reductionist), cross-disciplinary scientific research. These three observations are described in further detail in the following sections.

Ethics and Wicked Problems

Wicked problems typically test the limits of ethical analysis in business-as-usual and systems engineering approaches, which are concerned primarily with the actions of individuals in the context of professional groups. That is, traditional ethical norms typically hold the technologist to standards of responsible *conduct*, but limit the extent to which the individual should be held accountable for broader systemic *consequences* resulting from the application of technology, thereby permitting the individual to pursue technology unfettered by broader social concerns (Mitcham 1989). Clearly, as science increasingly becomes a social, institutionalized activity, it becomes impossible to parse responsibility for larger technological systems among the multitude of individuals that have participated in development of its components. As Allenby (2006) points out, it is "simply untenable" to ascribe responsibility to individual scientists for systems to which they have contributed, but are ultimately self-organizing, indeterminate, and beyond the individual's control. Under such circumstances, ethical considerations must be considered at the scale of the *collective*, which we refer to here as *macroethics*.

At the collective scale, disagreements with regard to the normative elements of wicked problems in inevitable in at least three characteristics areas: (1) problem formulation, (2) multiple but incompatible solutions, and (3) competing value systems or objectives. Although nearly universal acceptance of the necessity of ethical reasoning might be achievable in consideration of incompatible solutions and competing value systems, the ethical difficulties in problem formulation may be particularly non-obvious. Nevertheless, because sustainable engineering science problems are also wicked problems, formulation of sustainability problems requires value judgments regarding boundaries, goals, and definitions that are necessarily informed by some *ethical pre-positioning*. Therefore, sustainability scientists need to develop the requisite skills that enable them to identify, directly address, and deliberate with a "pluralism open to otherness" (Mitcham 1989) about ethical issues that arise in relation to new technologies.

Figure 1 is a macro-ethical tool that illustrates several points of ethical tension that define different interpretations of sustainability. In formulating *any* problem within the domain of sustainability, scientists must confront each of these axes on a multi-dimensional *Sustainability Sextant*. Each dimension is interrelated in the

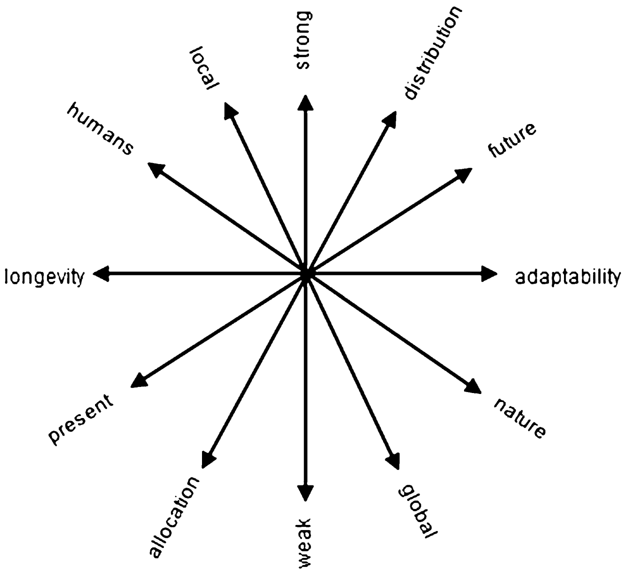

Fig. 1 Sustainability sextant

sense that some perspectives suggest or are more consistent with others. Nonetheless, the purpose of the *Sextant* is to guide individuals from their own points of view to those that may be foreign to them. Sources of tension include:

- The problem of preserving the status quo (or *longevity*), versus *adaptability* under changing circumstances (Seager 2008).
- The extent to which animals, plants, or other living systems (which we call *nature*) should be considered as intrinsically worthwhile, or only as instrumental to *human* needs.
- The distribution of risks and benefits of different technological interventions between *local* and *global* constituents. For example, in hazardous waste remediation, energy and resource expenditures that improve local conditions by removing hazardous materials may result in shifting risks to global populations—e.g., through carbon dioxide emissions (e.g., Sparrevik et al. 2011).
- Contrasting *strong* sustainability, which calls for conservation of resources in their original forms due to lack of substitutability, with *weak* sustainability, in which resources are regarded fungible and substitutable (Ayres et al. 2001). For example, strong sustainability views reject fish farming as a substitute for wild fish stocks, whereas weak sustainability might go so far as to accept processed protein sources (e.g., derived from soy) as protein substitutes in diets that historically relied upon fish.
- The degree to which the principal economic concerns in sustainability should be preoccupied with *allocation* of resources or *distribution* of benefits. While functioning economic systems must do both (Daly 1997), in the extreme the argument for efficient allocation conflicts with the ideal of equitable distribution.

- Lastly, the time frame of concern in sustainability is particularly contested. While one popular view is that sustainability problems should be considerably far-reaching into the *future*. However, the question of what is owed to future generations cannot be adequately addressed without understanding what sacrifices must be made in the *present* (Solow 1993).

At a minimum, sustainable engineering scientists must be able to recognize behavioral and cognitive patterns of macroethical significance, formulate macro-ethical problems, and employ the deliberative and moral reasoning skills necessary to work adaptively towards practical resolutions. As such, the macroethical reasoning skills required of a sustainable engineering scientist transcend mere conformance to the norms or codes of professional ethics necessary to responsibly carry out business-as-usual or systems engineering approaches (Allenby 2006; Seager and Selinger 2009). In sustainable engineering science, problems of technology are embedded in complex, self-organizing systems. Therefore, ethical issues may emerge at a scale much larger than that of the individual. Where moral dilemmas are not traceable to the actions of individuals, or even to the collective action of an organization, profession, or industry, they may result from the complex and dynamic *interaction* among many organizations and individuals. Consequently, they cannot be resolved without deliberation and collective action. The norms of professional ethics, which operate at the level of the individual decision-maker or organizations, are therefore inadequate to understand or identify macro-ethical issues germane to wicked problems generally, and sustainability in particular. The sustainability engineering scientist must acquire a *macroethical awareness* and the deliberation skills necessary to work through macro-ethical issues in concert with others.

Building Resilience instead of Managing Risk

Open-ended timeframes are an essential characteristic of wicked problems that must be addressed both by anticipation and adaptation. In this sense, wicked problems should not be thought of as problems to be solved, but *conditions to be governed.*[2] While anticipation aids in preparation of contingency plans, or mitigation of adverse consequences in the event of failure, adaptive strategies are particularly appropriate for complex systems in which surprises may emerge at scales outside those of ordinary observation. By contrast, the conservative sustainability response is a *risk analytic* approach that begins with hazard identification and follows with estimates of the probability and consequences of failure (NRC 2009). Among the strategies for mitigation of risk are monitoring and control systems, armoring, redundancy, and resistance. However, it is sometimes the case in complex systems that an effort to control one problem only creates new problems (Gunderson and Light 2006; Guston 2008). By contrast, sustainable engineering science borrows strategies from

---

[2] We thank Brad Allenby for this insightful way of reframing wicked problems as "conditions," which evokes a medical analogy with chronic diseases (such as Type I diabetes) that cannot be cured but can effectively be managed.

ecology such as diversity, adaptation, evolution, recovery, and renewal. These strategies are encompassed in an emerging approach that entails designing for *resilience*, which describes the ability of a system to respond to stressors without losing basic functionality or structure (Holling 1996). The most fundamental difference between the resilience strategies associated with sustainable engineering science and other approaches is the realization that not all hazards can be quantified, or even identified, in advance. In such cases, the likelihood of catastrophic failure may be exacerbated by ignorance of hidden risks. By contrast, the resilience approach attempts to build flexibility and adaptability into systems that are responsive to any stressor, albeit at the expense of temporary failures or disturbances that are (hopefully) recovered from quickly (Bossel 2000).

Mu et al. (2011) claim that habits or design heuristics learned in the business-as-usual and systems engineering paradigms (e.g., that have dominated the petroleum-based energy industry) are unsuitable for bioenergy systems due to the close coupling of biorefineries to complex ecological systems that are a source of stochastic disruptions. Analogous examples may be found in other industries (Sheffi 2007). For example, recent bankruptcies in the American automobile industry have caused manufacturers to rethink design of assembly plants. Although Japanese manufacturers generally did a better job of anticipating disruptions and design for flexibility (even in North American plants), historically the American factories have been optimized to produce only one or two models (using the same vehicle platform) at a time. However, volatility in gasoline prices, interest rates, and consequent consumer preferences led to the new strategy of flexible manufacturing, in which very different types of cars can be produced at the same assembly plant without retooling (Chappell and Truett 2009). Flexible assembly plants are more expensive, and consequently squeeze profit margins (especially in comparison to competitors that do not adopt flexible manufacturing). However, flexibility allows auto manufacturers to maintain sales by rapidly adapting their product mix to unpredictable market conditions. This example illustrates the trade-off that can exist between efficiency and resilience (Korhonen and Seager 2008). Still, there remain several instances in which engineered systems are only discovered to be coupled to complex ecological systems *after* existential catastrophe. These include the Deepwater Horizon explosion and the partial meltdown of the Fukishima nuclear reactors (Park et al. 2011). Therefore, an essential characteristic of adaptive strategies must be *anticipatory competence* (Wiek et al. 2011) that is capable of imagining possibilities (as opposed to estimating *probabilities*) and understanding the potential consequences of adaptive interventions.

Interactional Expertise

Wicked problems undoubtedly require cross-and trans-disciplinary approaches, particularly because each wicked problem is unique. Sustainable engineering science hypotheses, in particular, are often formed by integrating environmental, social, and economic considerations with knowledge of a core science or engineering discipline (Komiyama and Takeuchi 2006; Michelcic et al. 2003).

Therefore, sustainability scientists need to develop interactional expertise (IE) in disciplines directly related to sustainable development, such as economics, public policy, and thermodynamics. Over the last decade, humanities and social science scholars have tried to establish two basic truths about IE: (1) it is central to developing *every form* of scientific expertise; and (2) it is used at the beginning of *all* genuinely interdisciplinary collaborations (Collins 2010; Collins and Evans 2007; Gorman 2002; Collins et al. 2007).[3]

"Interactional" and "contributory" expertises are different, though related, types of expertise. Contributory experts are the class of professionals designated by the typical use of the word "expert." They develop specialist knowledge and skill through formal education and, in many cases, hands-on, experiential training and function at a recognized high level of ability. By contrast, interactional experts are not primary practitioners. They learn about a field, including its collective tacit knowledge, primarily by talking with the people who have acquired contributory expertise. The immersion enables interactional experts to obtain considerable discursive expertise in specialized domains, even though they usually lack the practical skills required to make the contributions that directly advance the relevant professions.[4] Through this discursive prowess, interactional experts demonstrate they can see the world from a specialist's perspective—i.e., proffer authoritative technical judgments, make insider's jokes, and raise devil's advocate questions that revolve around ideas typically known only to specialists in a field.

To acquire interactional expertise, students must obtain in-depth and linguistically communicable understanding of the concepts, conventions, cognitive styles, and tacit knowledge that allow these disciplines to function collectively. Without this synthesis, it will be difficult for students to reliably conduct original scientific research in fields like nanotechnology, climate science, and bioengineering that accord with the principles of sustainable development. Graduate programs that prioritize business-as-usual and systems engineering approaches over sustainable engineering science have the luxury of using established approaches to curricular

---

[3] Some of the discussion of interactional expertise and related concepts appeared earlier in an NSF white paper, "Clarifying the Developmental and Pedagogical Dimensions of Interactional Expertise as a Function of Social and Psychological Relations Between Tacit and Explicit Knowledge" written by David Stone, Evan Selinger, Chris Schunn, and Barbara Koslowski for an National Science Foundation workshop called, "Acquiring and Using Interactional Expertise: Psychological, Sociological, and Philosophical Perspectives."

[4] Given the focus of this paper, it is only possible to present a brief summary of interactional expertise that is unable to convey the nuance found in scholarly literature and emerging conversations. For example, it is often pointed out that contributory experts typically possess interactional expertise. Otherwise they would not be able to make technical judgments in their fields that display knowledge of the underlying paradigm; nor, in the case of many sciences, would they be able to communicate with experts working within their broader specialties. Furthermore, in recent list-serv discussion the term "special interactional expert" has been used to emphasize the fact that contributory experts also develop interactional expertise. They do so in the sense that many disciplines are so specialized that in-between experimentalists and theorists exist a wide range of people whom we would think of as contributory experts. These contributory experts, in fact, have very little direct contact with either the practical matters involved in the experimentation or the complex mathematics involved in the theorizing, and so, in fact, derive most of their ongoing expertise from dialogue and conversation among their peers. Special interactional experts, then, designates the category of interactional experts who are completely "non-practice-based."

development and teaching. By contrast, universities committed to sustainable engineering science must accept the challenge of developing novel pedagogical tools. The common attempt to foster integrative education by enrolling students in a series of introductory modules that cover a broad range of topics is likely inadequate for promoting the necessary cross-disciplinary training.

Unfortunately, no one has yet created a successful pedagogy of IE. Since IE involves mastering the *use* of language within a given domain, it uses tacit knowledge that cannot be fully explicated in terms of operational rules or through the application of formal knowledge. Because of its tacit dimension, IE is a skill that differs in kind from formal knowledge, and as such, it *cannot be acquired merely by reading texts*, *participating in lecture courses*, *or engaging with computer programs that provide portals into micro-worlds*. Indeed, ongoing feedback from contributory experts appears to be a prerequisite for obtaining IE. Furthermore, acquiring IE is time-consuming. This means that attempting to obtain it could derail a promising career in a primary discipline. Therefore, the type of educational experience that is needed must make the defining features of IE accessible and inexpensive.

While questions remain about how best to impart the needed tacit knowledge, it is clear that the focus needs to be on accelerating "linguistic socialization," the process that Collins associates with acquiring IE. It thus may be sensible to adopt pedagogical strategies from foreign language instruction (Berardy et al. 2011). These typically include techniques for obtaining: efficient memorization of words and phrases; grasp of semantics in written and oral forms of communication, including colloquialisms; knowledge of rules and cultural customs for structuring different types of conversational exchange; immersion experiences; and, appreciation of relevant cultural and historical considerations.

The challenges of conveying and building IE are daunting. Yet, sustainability science education in general, and sustainable engineering science in particular, have developed and successfully applied a variety of pedagogical approaches and tools to master these challenges, including reflective case encounters (embedding), cultural awareness rising techniques, team teaching, and others (Brundiers and Wiek 2010; Mulder et al. 2010).

Conclusion

Rittell and Webber (1973) formulated their original characterization of wicked problems while offering a critique of scientific expertise, which they deemed "doomed to failure" in the complex area of social planning. Similar criticisms have been levied against industrial-age science in the domains of ecology and economics, which, together with society, envelop sustainability problems. Despite rapid adoption of the rhetoric of sustainability in nearly all science and technology disciplines, there has been very little effort at universities and research institutions to adapt the scientific enterprise to meet the challenge of sustainability as a wicked problem. Initiatives attempting to establish research and educational programs in sustainability that account for the features and challenges outlined above meet resistance and reluctance but have also developed strategies to overcome individual and institutional barriers (Mulder et al. 2010; Wiek et al. 2011).

To clarify some of the fundamental ways that sustainability training can be enhanced, we identified three principal shortcomings within the dominant scientific outlooks towards sustainability, "business-as-usual" and "systems engineering," which limit the conceptual resources available for creating innovation within sustainability education:

1. A myopic focus on professional ethics to the neglect of ethical issues germane to the complex interaction of many groups with multiple or competing views, and a lack of sensitivity to the ethical pre-positioning that comes from being embedded in the norms that typify different approaches to scientific and engineering research; and,
2. A preoccupation with capability and efficiency as the goal of high technology that undermines system adaptability, diversity and flexibility (i.e., resilience) in response to stressors or surprises; and,
3. A paucity of pedagogical techniques for teaching and incentivizing acquisition of the interactional expertise necessary to work effectively across disciplinary boundaries.

While nascent attempts to foster a better understanding of what sustainable engineering science is and has the potential to be exist in the ethics and resilience literatures, scant attention has been paid to developing techniques for training sustainability scientists or applying sustainable engineering science to the development of technological systems.

Acknowledgments The authors would like to thank the comments of anonymous reviewers on an earlier version of this paper.

References

Allenby, B. (2006). Macroethical systems and sustainability science. *Sustainability Science, 1*, 7–13.

Ayres, R. U. (1998). The price-value paradox. *Ecological Economics, 25*, 17–19.

Ayres, R. U., van den Bergh, J. C. J. M., & Gowdy, J. M. (2001). Strong versus weak sustainability: Economics, natural sciences, and "consilience." *Environmental Ethics*, *23*, 155–68.

Berardy, A., Seager, T. P., & Selinger, E. (2011). Developing a pedagogy of interactional expertise for sustainability education. *Proceedings of the 2011 IEEE International Symposium on Sustainable Systems and Technology*, Chicago, IL, 16–18 May 2011.

Borgman, A. (1984). *Technology and the character of contemporary life: A philosophical inquiry*. Chicago, IL: University of Chicago Press.

Bossel, H. (2000). Policy assessment and simulation of actor orientation for sustainable development. *Ecological Economics, 34*, 337–355.

Brundiers, K., & Wiek, A. (2010). Educating students in real-world sustainability research: Vision and implementation. *Innovative Higher Education, 36*(2), 107–124.

Brundtland, G. H., & Khalid, M. (1987). *Our common future*. Oxford UK: Oxford University Press.

Chappell, L., & Truett, R. (2009). Slump shows who's flexible, who's not; Japanese manufacturers can soften the economic blows with their ability to add and subtract models in days rather than months. Now the Detroit 3 are primed to do the same. *Automotive News, 83*(6362), 13.

Clark, W. C. (2007). Sustainability science: A room of its own. *PNAS, 104*, 1737–1738.

Clark, W. C., & Dickson, N. M. (2003). Sustainability science: The emerging research program. *PNAS, 100*(14), 8059–8061.

Collins, H. (2010). *Tacit and explicit knowledge*. Chicago, IL: University of Chicago Press.

Collins, H., & Evans, R. (2007). *Rethinking expertise*. Chicago, IL: University of Chicago Press.

Collins, H., Evans, R., & Gorman, M. (2007). Trading zones and interactional expertise. *Studies in the History and Philosophy of Science, 38*(4), 657–666.

Connolly, S. (2007). Mapping sustainable development as an essentially contested concept. *Local Environment, 12*(3), 259–278.

Daly, H. E. (1997). *Beyond growth: The economics of sustainable development*. Boston, MA: Beacon Press.

Davison, A. (2001). *Technology and the contested meanings of sustainability*. Albany, NY: SUNY Press.

Dovers, S. (1996). Sustainability: Demands on policy. *Journal of Public Policy, 16*, 303–318.

Fiksel, J. (2006). Sustainability and resilience: Toward a systems approach. *Sustainability: Science, Practice and Policy, 2*(2), 14–21.

Funtowicz, S. O., & Ravetz, J. R. (1993). Science for the post-normal age. *Futures, 25*(7), 739–755.

Gallie, W. B. (1956). Essentially Contested Concepts. *Proceedings of the Aristotelian Society, 56*, 167–198.

Gorman, M. (2002). Levels of expertise and trading zones: A framework for multidisciplinary collaboration. *Social Studies of Science, 32*(5), 933–939.

Gunderson, L., & Light, S. S. (2006). Adaptive management and adaptive governance in the everglades ecosystem. *Policy Sciences, 39*(4), 323–334.

Guston, D. H. (2008). Innovation policy: Not just a jumbo shrimp. *Nature, 454*, 940–941.

Healy, M. L., Dahlben, L. J., & Isaacs, J. A. (2008). Environmental assessment of single-walled carbon nanotube processes. *Journal of Industrial Ecology, 12*(3), 376–393.

Holling, C. S. (1996). Engineering resilience vs. ecological resilience. In P. C. Schulze (Ed.), *Engineering within ecological constraints*. Washington, DC: National Academy Press.

Iijima, S. (1991). Helical microtubules of graphitic carbon. *Nature, 354*, 56.

Kates, R. W., Clark, W. C., Corell, R., Hall, J. M., Jaeger, C. C., Lowe, I., et al. (2001). Sustainability science. *Science, 292*(5517), 641–642.

Keefe, R., Griffin, J. P., & Graham, J. D. (2008). The benefits and costs of new fuels and engines for light-duty vehicles in the United States. *Risk Analysis, 28*(5), 1141–1154.

Komiyama, H., & Takeuchi, K. (2006). Sustainability science: Building a new discipline. *Sustainability Science, 1*, 1–6.

Korhonen, J., & Seager, T. P. (2008). Beyond eco-efficiency: A resilience perspective. *Business Strategy and the Environment, 17*(7), 411–419.

Lovelock, J. E. (1971). Atmospheric fluorine compounds as indicators of air movements. *Nature, 230*, 379.

Lovelock, J. E., Maggs, R. J., & Wade, R. J. (1973). Halogenated hydrocarbons in and over the Atlantic. *Nature, 241*, 194–196.

Michelcic, J. R., Crittenden, J. C., Small, M. J., Shonnard, D. R., Hokanson, D. R., Zhang, Q., et al. (2003). Sustainability science and engineering: The emergence of a new metadiscipline. *Environmental Science and Technology, 37*, 5314–5324.

Mitcham, C. (1989). In search of a new relation between science, technology, and society. *Technology in Society, 11*, 409–417.

Mu, D., Seager, T. P., Rao, P. S. C., Park, J., & Zhao, F. (2011). A resilience perspective on biofuels production. *Integrated Environmental Assessment & Management*, *7*(3), 348–359.

Mulder, K. F., Segalas-Coral, J., & Ferrer-Balas, D. (2010). Educating engineers for/in sustainable development? What we knew, what we learned, and what we should learn. *Thermal Science, 14*(3), 625–639.

Norton, B. G. (2005). *Sustainability: A philosophy of adaptive ecosystem management*. Chicago, IL: University of Chicago Press.

NRC. (2009). *Science and decisions: Advancing risk assessment, committee on improving risk analysis approaches used by the U.S. EPA*. Washington, DC: National Academy Press.

Oberdörster, G., Oberdörster, E., & Oberdörster, J. (2005). Nanotoxicology: An emerging discipline evolving from studies of ultrafine particles. *Environmental Health Perspectives, 113*(7), 823–839.

Oberdörster, G., Stone, V., & Donaldson, K. (2007). Toxicology of nanoparticles: A historical perspective. *Nanotoxicology, 1*(1), 2–25.

Park, J., Seager, T. P., & Rao, P. S. C. (2011). Lessons in risk- versus resilience-based design and management. *Integrated Environmental Assessment & Management*, *7*(3), 396–399.

Raffaelle, R., Robison, W., & Selinger, E. (2010). *5 Questions: Sustainability ethics*. USA: Automatic/VIP Press.

Rittell, H. W. J., & Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy Sciences, 4*, 155–169.

Rowland, F. S., & Molina, M. J. (1975). Chlorofluoromethanes in the environment. *Reviews of Geophysics, 13*(1), 1–35.

Sarewitz, D., & Nelson, R. (2008). Three rules for technological fixes. *Nature, 456*, 871–872.

Seager, T. P. (2008). The sustainability spectrum and the sciences of sustainability. *Business Strategy and Environment, 17*(7), 444–453.

Seager, T. P., & Selinger., E. (2009). Experiential teaching strategies for developing ethical reasoning skills relevant to sustainability. *Proceedings of the 2009 IEEE International Symposium on Sustainable Systems and Technology*. Phoenix AZ, 18–22 May 2009. Available online at http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?tp=andarnumber=5156721andisnumber=5156678.

Seager, T. P., & Theis, T. L. (2003). A thermodynamic basis for evaluating environmental policy trade-offs. *Clean Technologies and Environmental Policy, 4*, 217–226.

Seager, T. P., & Theis, T. L. (2004). A taxonomy of metrics for testing the industrial ecology hypotheses and application to design of freezer insulation. *Journal of Cleaner Production, 12*, 865–887.

Sheffi, Y. (2007). *The resilient enterprise*. Cambridge, MA: MIT Press.

Simon, J. L. (1996). *The ultimate resource 2*. Princeton, NJ: Princeton Univ Press.

Solow, R. (1993). Sustainability: An Economists perspective. In R. Dorfman & N. S. Dorfman (Eds.), *Economics and the environment: Selected readings*. New York, NY: Norton.

Sparrevik, M., Saloranta, T., Cornelissen, G., Eek, E., Fet, A. M., Breedveld, G. D., et al. (2011). Use of life cycle assessments to evaluate the environmental footprint of contaminated sediment remediation. *Environmental Science and Technology, 45*(10), 4235–4241.

Talwar, S., Wiek, A., & Robinson, J. (2011). User engagement in sustainability research. *Science and Public Policy, 38*(5), 379–390.

Theis, T. L., Bakshi, B., Clift, R., Durham, D., Fthenakis, V., Gutowski, T., Isaacs, J., Seager T. P., Wiesner, M. R. (2011). A life cycle framework for the investigation of environmentally benign nanoparticles and products. *Physica Status Solidi Rapid Research Letters*. doi:10.1002/pssr.201105083

Wiek, A., Withycombe, L., Redman, C. L., & Banas Mills, S. (2011). Moving forward on competence in sustainability research and problem-solving. *Environment: Science and Policy for Sustainable Development, 53*(2), 3–12.

Wiek, A., Zemp, S., Siegrist, M., & Walter, A. (2007). Sustainable governance of emerging technologies—Critical constellations in the agent network of nanotechnology. *Technology in Society, 29*(4), 388–406.

Woodhouse, E., & Sarewitz, D. (2007). Science policies for reducing societal inequities. *Science and Public Policy, 34*(2), 139–150.