The Systemic Correlation Between Mental Models and Sustainable Design: Implications for Engineering Educators*

LINDA VANASUPA
Materials Engineering Department, California Polytechnic State University, San Luis Obispo, CA 93407, USA. E-mail: lvanasup@calpoly.edu

ROGER BURTON
Center for Teaching and Learning, California Polytechnic State University, San Luis Obispo, CA 93407 USA.

JONATHAN STOLK
Mechanical Engineering and Materials Science, Olin College of Engineering, Needham, MA 02492 USA.

JULIE B. ZIMMERMAN
Yale School of Forestry and Environmental Studies & Chemical Engineering Program, Yale University, New Haven, CT 06505, USA.

LARRY J. LEIFER
Center for Design Research, Stanford University, Stanford, CA 94306, USA.

PAUL T. ANASTAS
Center for Green Chemistry and Engineering at Yale, Yale University, New Haven, CT 06505, USA

Many studies have illuminated our understanding of the kinds of competencies and behaviors exhibited by effective designers. Against the backdrop of global challenges made more urgent by unintentional negative impacts of engineered products and systems, however, we are left to deduce that our ways of educating engineering designers is fundamentally flawed. We assert that one can trace the cause of our collective, unintended negative consequences to the mental models of reality that we consciously or unconsciously carry. In this paper, we present the case for developing awareness and facility with mental models. We also suggest an alternate mental model as the foundation for sustainable design. This model depicts reality as embedded systems of economies inside society and inside the environment. We also discuss how the engineering educator can use the model to build a foundation for holistically viewing design for sustainability. Student responses to a course based on the proposed ideas are also presented as evidence that students' can value mental models and that working with them effectively changes their world conception.

Keywords: systems thinking; sustainability; sustainable design; mental models; design

1. INTRODUCTION

GIVEN THE MAGNITUDE of twenty-first century challenges, it is increasingly clear that effective engineers will need to be capable of designing for sustainability; that is, they must be able to engage in 'sustainable design.' Unfortunately, 'sustainable' and 'design' are terms that share an ambiguous heritage that is not clarified by combining them into 'sustainable design.'

Sustainability, which is being approached by some as an emerging science [1], is viewed by some engineers as a design constraint [2]. However, it is a constraint that defies simple evaluation. Its *indicators*, which engineers may view as measures analogous to *design specifications,* can include qualitative measures such as 'Reducing the gap between rich and poor,' 'Conserving and enhancing the natural environment,' and 'Enhancing community participation.' [3, 4]. These measures highlight the fact that sustainability encompasses societal, environmental and economic dimensions as well as the interactions between them. These measures also represent a degree of dynamic complexity not encountered in traditional engineering performance criteria. Along with the (U.S.) National Academy of Engineering's Committee on Grand Challenges for Engineering, who identified four categories of engineering challenges (sustainability, health, safety, and the joy of living), these indicators underscore the shifting identity of engineers in society from 'designers of widgets' to 'co-designers of a healthy, thriving, global future.'

This shift to a more systemic design process that must consider the global complexities of the proposed design is itself a paradigmatic shift. As

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such, it is likely to involve the human dynamics described by Thomas Kuhn in his seminal book, *The Structure of Scientific Revolutions* [5]. This includes vehement resistance to the new paradigm. It also results in counterproductive actions. For instance, if your assumptions about growth are producing the consequences that are viewed as unsustainable, more growth cannot produce a different result. Oddly however, in the process of a paradigm shift doing more of what is already being done is exactly what happens first. Kuhn asserts that the eventual acceptance of a new paradigm comes not through a preponderance of convincing evidence, but through an examination of values related to the consequences of adopting or rejecting the new paradigm. It is useful for educators to be mindful of this transitional process as students and faculty will likely experience the internal conflict inherent to our professions' shifting identity.

The intent of this paper is to contribute to the broader conversation around how we enable that particular shift in identity. We begin with a consideration of what has led to our current unsustainable state. We then describe a mental model that we feel is essential to sustainable design. The final section describes the use of the model in a teaching situation. Student comments from a senior-level engineering course that was based on the teaching ideas presented in this paper are also included.

2. UNSUSTAINABLE DESIGN AS A SYSTEMIC CONSEQUENCE OF OUR HISTORICALLY VALID MENTAL MODELS

There now exists substantive scientific evidence from a range of disciplines that points to global human activity as the source of rising concentrations of atmospheric carbon dioxide (CO_2) [6]. The higher CO_2 content directly increases CO_2 absorbed by the ocean, increases its acidity, and kills the oceanic foundation of the global food chain [7]. Aside from the debated impact of rising temperatures, it is clear that destroying the basis of the global food chain threatens the system of biological services that support human and non-human life on earth. Simply put, our fossil fuel-intensive state is not sustainable if we intend to sustain the human species.

It is hard to imagine that the global-scale, negative impacts are by *design*. Clearly, they must be unintended consequences of designers. While the exact cause of our collective, global unsustainability is not solely the fault of engineers, engineering advances have inadvertently contributed to the current state. William Perry, chair of the Committee on Engineering's Grand Challenges (National Academy of Science, U.S.) says that 'engineers must save the world, in some cases, from the harm that technology enabled.' [8]. Because public safety is at the core of an engineer's goal, we must ask,

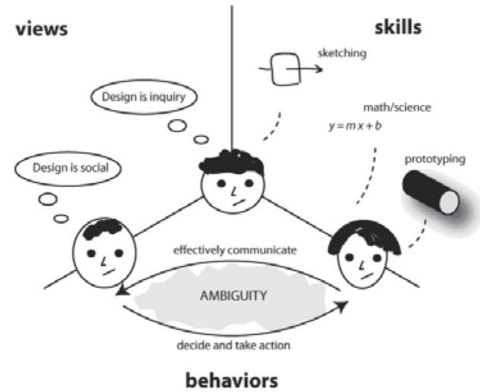

Fig. 1. Summary of the views, skills and behaviors of an effective designer. adapted from Dym et al. [8].

'Why are we as engineers currently and collectively engaged in unsustainable design?'

As an activity, design has been well studied. Dym et al. posit that *effective* designers exhibit the set of views, skills and behaviors that we have summarized in Fig. 1 [9]. Effective designers see design as a process of inquiry while being mindful of the 'big picture,'; they possess the cognitive, visual, verbal and psychomotor skills to communicate in several different 'languages' of design (e.g., sketching, prototyping, physical laws of nature, engineering science); and they are able to collectively make decisions in the face of ambiguity. While this is a helpful characterization of 'designing,' what is hidden is the external learning conditions and internal thought processes that ultimately lie at the root of what we are currently experiencing as unsustainable design.

To look at the cause of design that is unsustainable, we turn to Aristotle's ideas on causality. He asserts that the source or reason behind the existence of any thing or condition can be traced to four types of causes: material cause, efficient cause, formal cause and final cause [10], Fig. 2. In the context of designing products or systems, these refer to decisions about the materials ('material cause'), decisions about the process in which it is created ('efficient cause'), decisions about the actual form of the product ('formal cause'); and the decisions about the purpose, goal or intended context of service of a designed artifact ('final cause'). Material choices and process choices that are somehow harmonious with environmental and social systems will be undermined if the form or the purpose is inherently unsustainable. For example, grocery store patrons are confronted with the choice of paper disposable bags or plastic disposable bags for their purchases (i.e., 'material' cause). However, any benefits of the material choice are made irrelevant by the systemically damaging effect of the design (i.e., 'formal' cause) of a system. The system requires a constant supply of energy, materials and resultant pollutants to manufacture packaging that will be used once and disposed. What is the intent of such

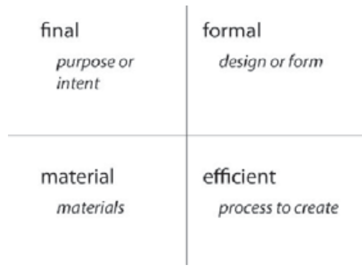

Fig. 2. Aristotle's four types of causality and the design decisions related to them (in italics).

system? It may be something like, 'Serve the economy by creating a disposable bag market,' This purpose does not consider the finite nature of energy and materials from the environment nor the infinite sink required for resultant waste with respect to the product life cycle. As designers for sustainability, we need the four causalities to align, recognizing that that the final cause is most influential in the outcome.

Furthermore, underlying all four of these causalities are individuals' beliefs and understandings, or 'mental models.' When these mental models or worldviews are commonly accepted, they are considered paradigms. There is a great deal of evidence that individuals' actions (e.g., decisions, behavior) are strongly influenced by paradigms or their mental models of reality [11–13], whether they are conscious of them or not. From a systems point of view, this is analogous to the principle that the system's structure determines its behaviors. By extension, a *designer*'s decisions proceed from the mental models that they hold. This principle has been validated in the behavioral sciences [14]. We assert then, that existing mental models have led to unsustainable design.

To examine how mental models have led to unsustainable design, consider the filtering effect of mental models. Oftentimes, mental models act as filters for what people (and by default, designers) observe and remember (Fig. 3). One's mental model thus limits the data set from which one can draw for making decisions. This is usually very helpful. It also restricts the outcome to that which is already known; the result is a repetition of known solutions, particularly when mental models are neither examined nor altered.

Within the conversation about sustainability, many often refer to the 'triple bottom line' mental model–net gains in social, economic and environment considerations as a design or decision making criteria. This is depicted with a set of separate but overlapping circles as shown in Fig. 4. In the language of Venn diagrams, these three circles imply three separate systems that have overlapping regions. Sustainable design is characterized as the region where all three systems overlap.

While some may view this model as simply a convenient way of presenting the challenge of sustainable design, we contend that the consequences of this mental model are unsustainable design decisions. The reason is that it misrepresents the physical or thermodynamic relationships of the economic, societal or environmental systems. The consequences are design decisions that are misaligned with the natural order of things. For example, the economy has no meaning outside the confines of society, nor can either exist outside of the physical confines of the environment. However, if one holds a mental model like Fig. 4 that depicts an economic system wholly separate from both society and the environment, they may make decisions that are inconsistent with nature. For example, they may choose to create a product in service of the economic system while simultaneously externalizing the harm of serving the economy to the social and environmental system. Similarly, using a schematic of an arrow parallel to the earth's surface to represent the force

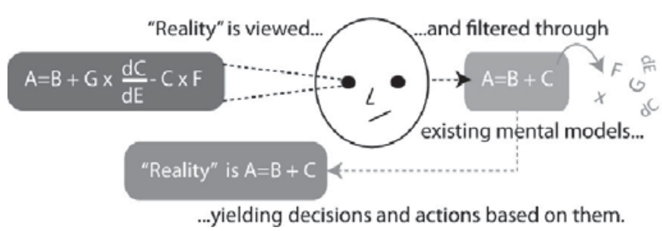

Fig. 3. Mental models serve as filters for reality, oftentimes defining the observers' data set from which he draws conclusions.

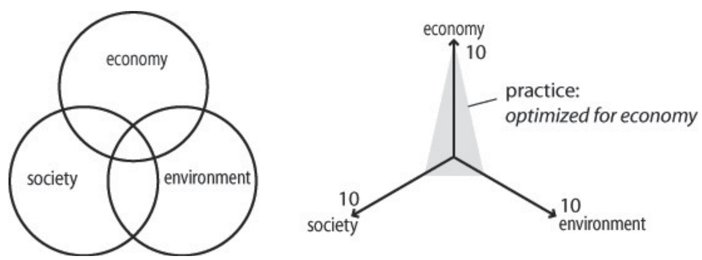

Fig. 4. Separate economic, societal and environmental systems.

of gravity would imply a gravitational force relationship to earth that was not accurate; Consider how this misrepresentation would affect designs if it were adopted as a mental model of reality. We submit that even in simplified depictions of concepts like the force of gravity, engineering educators normally avoid models that violate what we observe to be physical realities. We should practice the same level of care in the models we use to depict the concepts for sustainable design.

The model in Fig. 4 also implies an accounting system where one can weigh and trade-off the gains in between these three categories, resulting in three 'bottom lines.' It implicitly treats the environment, society and the economy as separate, competing and substitutable for one another. In practice, the often-unstated mental model is a set of three axes (Fig. 4, right) along which designers must optimize and balance. To illustrate, consider axes that go from zero to 10. Optimizing the tradeoffs in the triple bottom line is much like distributing an insufficient number of points (e.g., 17) across the three axes. Companies frequently defer to the economic 'bottom line' at the expense of societal and environmental concerns within the product or system life cycle. The consequence is short-term economic gain with long-term damage to the social and environmental systems required to create and 'consume' the product—eventually destructive to the economic system and thus counterproductive to the original purpose. This phenomenon illustrates one of the active questions around sustainable design: Where should we place the economic, environment, societal and temporal system boundaries?

The view of the economic, social and environmental systems as separate interests prevents one from seeing integrated approaches or leads one to make detrimental design choices. For example, suppose a designer was asked to design a system to protect workers from exposure to toxic vapors in the workplace. By viewing these workers as isolated within a conceptual system boundary, one solution could be to install some kind of vent that removes vapors from the worker's system to 'the surroundings.' However, if this vent moves the vapors to the public and environment at large, it has created a different problem. Once this vent system is implemented it is often the case that the '*solution*' to such consequences would be further engineering using the same line of thinking. We might try to deal with the vapors in the public space, rather than addressing the vent system or even the industrial process producing the vapors originally. That process replicates itself outward to a point of collapse wherein the unsustainability becomes immediately apparent in time and space. Essentially we naturally seek to conserve our successful engineered solutions. By using an integrated approach, one might seek to instead re-design the system so that toxins were not used at all.

We suggest that the mental model in Fig. 4 contributes to unsustainable design. Evolving to a new mental model creates the possibility of innovation in design, of thinking at a different level than the one that initially created the problem, as suggested by Einstein. One normally has the choice to do this when they encounter data that conflicts with their prevailing model. Simply put, the confrontation with a different viewpoint has the potential to bring one's unexamined model to light. However, this requires one to be willing and able to temporarily suspend their existing viewpoint (or equivalently, paradigm). The inability or unwillingness to do so makes the conflicting data difficult or even impossible to perceive. According to Kuhn, we literally delete data or distort it to fit our mental model [5]. However, the act of resolving the conflict into a reconstructed mental model is, in fact, the process of learning as described by learning theorists [15]. When viewed this way, one could argue that a key role of an educator is to enable seeing, examining and evolving one's mental models, particularly if the educator is seeking to cultivate the ability to innovate.

Facility with mental models is thus important for individual learning [16] and the ability to innovate. In reference to design, which is often a team-based process, facility with mental models is particularly important. Sharing mental models within teams has been shown to aid positive behavior and performance [17–19]. We suggest, then, that the leverage for producing a fundamentally different outcome of the design process, i.e., sustainable design, lies in creating facility with and establishing a shared set of appropriate mental models that serve to aid better decisions for sustainable design. Ultimately, replacing existing models with others reduces to contrasting and weighing the consequences of holding each. This involves developing the capacity in ourselves, as learners, to engage in 'cross model' conversations. As we have suggested, this means not only a capacity to recognize and suspend our own mental models, but also to productively engage in the interaction of multiple models. In such a process it is the very areas in which models seem to constrain one another or even conflict that creates the context for a deeper inquiry. That deeper inquiry is the process that leads to revealing the larger systems in which our design is embedded. We contend that an understanding of these systems is an essential competency of sustainable design. In the following section, we describe what we believe to be a foundational mental model that promotes the transition to designing for sustainability.

3. AN EMBEDDED SYSTEMS MODEL OF REALITY AS PARADIGM

A model that more accurately reflects the natural relationships between society, economy and environment is one that views these three systems

Fig. 5. Embedded systems model of reality.

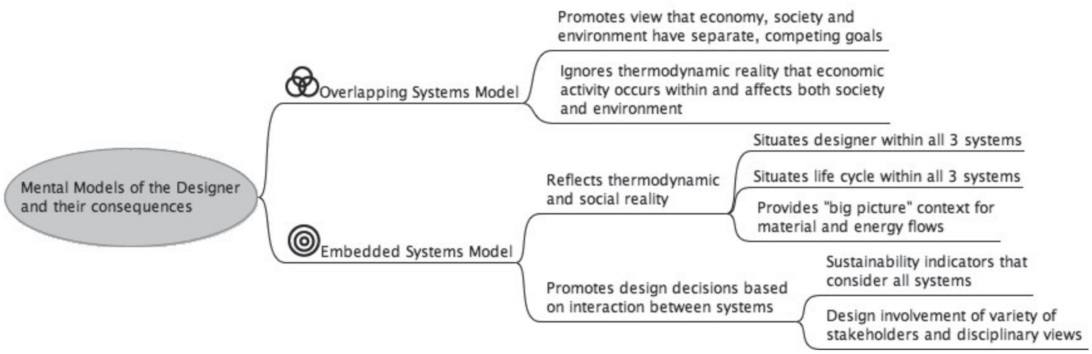

Fig. 6. Mental models and their consequences.

as embedded systems: the environment is the system in which society entirely resides; the economy is a wholly-owned system within society. The United Kingdom was among the early proponents of this model through their primary and secondary education campaigns in early 2000. In Fig. 5, we illustrate how the model is built by beginning with the entire earth as the physical equivalent of the environmental system. As shown in Fig. 5, this model derives its validity from the physical reality that society lives on the environmental system we call earth. Additionally, it visually implies the fact that the economic system is a human-made system of trading goods and services that only has meaning within the social system.

By using this embedded systems model as the starting point, sustainability of the parts of reality that are constrained by thermodynamics (e.g., material and energy) can take on a simple meaning that is connected to the laws of thermodynamics. For example, the environment is essentially a closed thermodynamic system (i.e., it can exchange energy with its surroundings, but it cannot exchange a significant mass to affects its own thermodynamic state). The law of mass balance implies that all material resources used in the economy for products or processes must come from the environment; additionally, the environment must act as a sink for all material wastes that result from the economy. It is also clear that society, on the whole, can be exposed to all that is within the environment. (It may not be that all are equally exposed and this fact leads to a further opportunity to discuss the fairness of who is and is not exposed to toxins in the environment.) Herman Daly's criteria [20] to sustain the integrity of the environmental system become quite logical:

- For renewable resources, the consumption rate must not exceed the regeneration rate (*promotes continual availability of renewable resources)*;
- For non-renewable resources, the consumption rate must not exceed the rate of substitution by renewable resources (*avoids depletion of non-renewable resources)*;
- For pollutants, the rate of emissions must not exceed the rate at which they can be either detoxified or absorbed by natural systems *(averts accumulation of toxins in the environment)*.

There are also parallel principles that guide design decisions for the social and economic dimensions of sustainability [21].

The model in Fig. 5 also illuminates the common-sense basis of the first of the 12 Principles of Green Engineering: *Design inherently benign systems* [22]. Any designed system will be physically situated in a shared social and environmental commons, so inherently benign systems serve to preserve the larger environmental system on which the other two systems depend.

In Fig. 6, we highlight the different consequences of using these two different mental models as concepts to depict sustainable design. As stated, the strength in the embedded systems model is its resonance with the thermodynamic and societal realities of our social, economic and environmental systems. It also promotes design decisions based on the true relationship and interaction between these systems. In the section that follows, we describe how the embedded systems model could be used by engineering educators.

4. USE OF EMBEDDED MODEL IN TEACHING

4.1 Situating the future engineer within the system

The embedded systems model is useful as a schematic to introduce our global reality and ask engineering students to locate themselves as engineering professionals in this depiction of reality. One activity that we have tested is to provide small groups of engineering students (typically four or fewer students) with the Preamble and Fundamental Canons of the U.S. National Society of Professional Engineers Code of Ethics (see Appendix). We then ask them to consider that the life cycle of an engineered product or process takes place wholly within the economy. Then, they are asked to identify the end point in the product or process life cycle in which the designing engineers are no longer responsible for the safety, health, and welfare of the public. Groups are given 20–30 minutes to reach a consensus. It is critical that students are given the time to dialogue with one another. It is also critical that faculty allow the students to draw their own conclusion without penalty or judgment for 'correct' or 'incorrect' answers, since the intent is to further one's ability to reason and reach a greater understanding of the relationship between their professional values, their own values and that of others. The activity usually invokes differences in viewpoints (mental models) and the opportunity to resolve these through a process of inquiring into others' points of view. It is also important that groups be given the opportunity to report their results to others. By reporting their own conclusion and hearing that of other groups, they are usually exposed to another level of conflicting views. In terms of Aristotle's four types of causality, this particular activity is intended to refine students understanding of their own 'final' cause or purpose as engineers and its interplay with the 'formal' cause or design.

Incidentally, one author (LV) has discovered that engineering students frequently need coaching on how to productively dialogue around differences of viewpoints. Some students are only exposed to unproductive modes of group processing: asserting their view as reality, declaring the reasons why their view is superior, identifying the reasons why other viewpoints are inferior and voting. Consensus requires each to openly listen and inquire for genuine understanding about the mental models that underlie another's viewpoint.

The point of such a process is not to categorize mental models as 'right' or 'wrong,' but to reveal the pre-existing mental models at play, understand something about why those are present and their resultant design consequences. We propose that distinguishing such models and understanding the implications in the design process, as well as actively applying them in a collaborative fashion forms the basis of the emergent design capability needed for sustainability. Essentially this is a process of individual and collective reflection. The results of at least two recent studies on U.S. engineering undergraduates' epistemological development suggest that reflection is not efficaciously cultivated in the current U.S. incarnation of engineering education (education in other countries may be different) [23, 24]. In the reflective process that we are suggesting, students are asked to become more aware of their own assumptions, taken as truth, during design.

Eliciting and unpacking one's mental models can be approached in a wide variety of ways. One way is to engage in a design exercise with fairly radical constraints about some aspect of the design. This could be something about the design space, the assumptions or even the outcome. When President John F. Kennedy declared that the United States would send a man to the moon by the end of the 1960's decade, this was so counter to the presumed facts in the design space that it challenged and made explicit a whole host of implicit mental models (e.g. there is no metal that can withstand the heat of re-entry, space vehicles should be made of metal, etc.). This 'counter-to-fact' design process challenges the student to understand what they view as the factual basis for the design consideration. They then can begin to examine the consequences of their existing mental models.

4.2 Situating the design process within the system

The embedded systems model of reality serves as a starting point for introducing the concept of sustainable design. In this model, it is clear that sustainable design must inherently address the interactions between the social, economic, and environmental systems. From an engineering design standpoint, this implies the need to develop design specifications, which are akin to sustainability indicators. Early sustainability pioneers suggest that sustainability indicators encompass three basic dimensions [5] which are easily understood by the embedded systems model depiction: the universal sufficiency of real human welfare (i.e., well-being), the sustainability of environmental integrity, and the ratio between the two, which acts as a measure of the efficiency of converting natural capital to real human welfare. Mathematically, we can conceptually express these in ratio form:

$$\left.\begin{matrix} \textit{sufficiency}\{ \\ \textit{sustainability}\{ \end{matrix} \frac{\text{real human welfare}}{\text{environmental integrity}}\right\} \begin{matrix} \textit{efficiency of} \\ \textit{conversion} \end{matrix} \quad (1)$$

In our nascent collaboration for village-scale sustainable design (www.sustainnow.org), the authors (LV, RB, and JS) have attempted to develop individual sustainability indicators. This is a daunting task that underscores the complexity and ambiguity of designing for sustainability. However, in the absence of attempting to use these indicators, designing for sustainability can inadvertently default to the current thinking of separate but overlapping economic, societal and environmental systems (Fig. 4).

There are at least two useful activities involving equation (1), both of which are aimed at refining the engineering students' 'final' cause, or purpose. One is to simply ask a group of students to develop a set of personal sustainability indicators for all three dimensions expressed in equation (1). This is most useful as an individual assignment that requires individual reflection and later group processing. In the group processing, students are again confronted with different viewpoints. The activity serves to promote new kinds of thinking about design. A variation on this exercise is to have individuals develop indicators for a classmate as if the other were the object of their design process. The designer would then report the results to the 'object' (classmate). What immediately surfaces is the invasive feeling of having another design your life. The lesson here is that sustainable design is best enacted as participatory or collaborative design with the stakeholders. The group dialogue about results fosters individual development and enriches the design space. The second activity is to ask the students to compare the goals embodied in equation (1) with the (U.S.) National Society of Professional Engineers 'Engineer's Creed.'

> *As a professional engineering, I dedicate my professional knowledge to the advancement and betterment of human welfare. I pledge:*
>
> - *To give the utmost of performance;*
> - *To participate in none but honest enterprise;*
> - *To live and work according to the laws of man and the highest standards of professional conduct;*
> - *To place service before profit, the honor and standing of the profession before personal advantage, and the public welfare above all other considerations.*

After comparison, have students identify where the professional pledge is most resonant with the goals of the indicators in equation (1). One could posit that the strongest resonance is in the universal sufficiency of real human welfare. But students (and faculty) may see otherwise. A variation on this activity is to state that the role of an engineer is to develop technology and ask them to justify this view using the creed and describe where that fits into the sustainability indicators of equation (1). Again, this is an activity that does not have definite correct and incorrect answers, but potentially has great value in developing facility with mental models

The embedded system serves as a schematic of the whole earth system in which the process of design takes place. While it is rare that a graduate would be engaged in a design for the entire earth system, it is certain that global conditions will impact their professional life, so the health of the global system should be explored. For example, while students may easily grasp the concept of balancing consumption rates with regeneration rates, the students may not be aware that according to Wackernagel et al., the global economy has been in an annual position of 'depletion' since the 1990 [25]. Wackernagel et al.'s analysis indicates that our annual global activity has exceeded earth's biocapacity to replenish the inputs that we have used and absorb the wastes that we have produced. In others words, by analogy to a bank account, our annual global expenditures are about 140% of our annual income. This implies that we are either eating into the principle (our natural capital) or accumulating debt. In practice, the increasing concentration of atmospheric carbon dioxide is a reflection of our accumulated debt for absorbing our waste from using fossil fuels. An activity that can be done after providing students with these facts is to ask students to provide strategies for improving the indicators reflected in equation (1). Depending on the background and awareness of the students, the response can range from superficial ideas on how to improve environmental integrity to much deeper questions about the meaning of real human welfare, environmental integrity, how any of it is measured and so on. This activity serves to ground these questions in the scientific understanding of the system's current health.

The embedded systems model can also be used to illustrate a big-picture understanding of global energy flows as shown in Fig. 7. This simple picture helps to reinforce several ideas. One is that we have a great excess of incoming solar energy. The other is that material flows remain within the environment.

This big-picture view also serves to invoke a question of scale: At what scale (i.e., system boundary) do we attempt to design sustainably? Holling contends that sustainability describes the 'capacity to create, test and maintain adaptive capability' [26] (p. 390). A consideration of sustainability must then include environmental, social, and interacting environmental-social systems, which are self-organized along shared scales of time and space and interdependent upon one another [27]. Sustainability practitioners also advance the view that sustainability can only be accomplished at a large, systems level, such as a village or town [28]. We must ask ourselves if sustainability makes sense at the 'product' level? Probably not as a quantitative design specification; however, it is likely that the failure to consider these broader impacts of engineered products has contributed to the unsustainable treatment of natural resources and inadvertently exacerbated global, social inequities.

The embedded systems model, by explicitly depicting the economy within society suggests that sustainable design solutions leverage factors

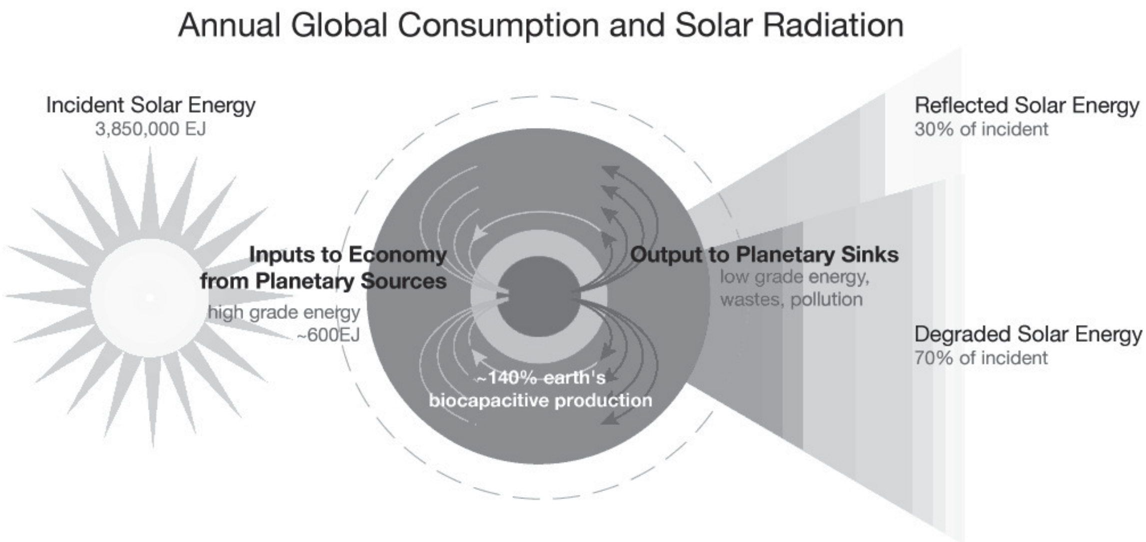

Fig. 7. Superposition of annual material and energy flows onto the embedded model of reality. Data on the incident solar energy comes from Vaclav [28]; the energy inputs to the economy are derived from the Energy Information Administration [29]. Biocapacitive production data is from Wackernagel et al. [25].

from the social knowledge domain. While it is common practice to consider human factors in design, we propose that sustainable design draws upon the social domain in uncommon ways. Within the embedded system framework, one can easily see that the health of the economic system depends on the health of the social and environmental systems in which it is embedded. If the engineering designer is lead to consider the health of all three systems, it becomes obvious that the domain knowledge from these other systems is needed, establishing the value of these other perspectives.

A mental model of sustainable design that may be helpful in this regard is the parable of three blind men attempting to describe to one another what an elephant is. In this parable, each man is touching a part of the elephant, but the elephant itself is so large, that no one has a complete understanding. One stands at the trunk and insists an elephant is like a tube, one stands at its side and insists that it is smooth and flat, the third stands at a leg and reports that an elephant is like a tree trunk. In this context, the problem that is trying to be solved through sustainable design is the elephant and the three blind men are those from different disciplinary perspectives. Each has a legitimate and valid viewpoint, yet it is incomplete. What is required for them to collectively 'see' the problem is for each to recognize that they only possess a limited view and that the others are needed for a more complete picture. The simple premise here is that no one point of view can describe something fully. (Incidentally, we note with humility that a sum of all the reductionist viewpoints cannot provide a complete understanding of the integrated system either.) In the same way, effective sustainable design requires that we are aware of our limited perspective and that we broaden our understanding through the perspec-

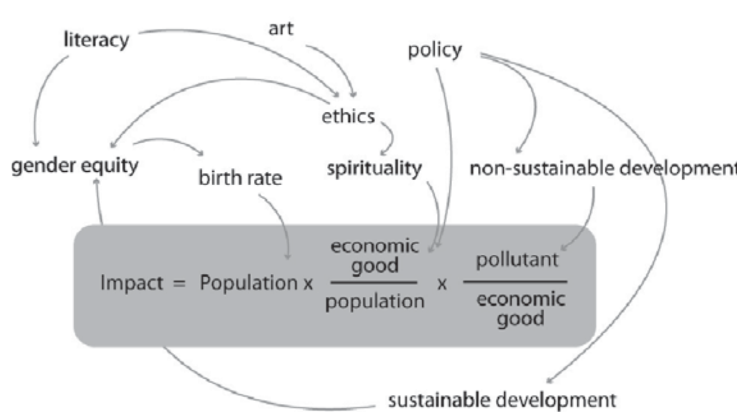

Fig. 8. The IPAT equation with expanded set of inputs through a casual loop diagram. This illustrates the value of other disciplinary perspectives for sustainable design.

tive of others. Valuing other disciplinary perspectives may seem obvious to the expert designer, but studies of engineering students reveal their low-level of valuation of perspectives outside of engineering or the physical sciences [30, 31]. New mental models like the embedded systems model and the parable of the three blind men and the elephant can aid design faculty in their work to illustrate the value of others' perspective, particularly those from the liberal arts side of the world.

Additionally, to underscore the importance of the social perspective in design, faculty can powerfully show the limits of technology for 'solving' the sustainability problem. A simple way to do this is to use Ehrlich and Holdren's Impact-Population-Affluence-Technology (IPAT) equation [32]. In this equation, represented in Fig. 8, Affluence (economic good/population) represents consumption patterns and Technology (pollutant/economic good) captures damage incurred by the methods used to achieve the economic goods that are consumed. Asking students to analyze the IPAT equation using existing population, affluence and technology trends reveals the dramatic result that we cannot in fact reduce our impact to sustainable levels using linear ways of thinking. For example, the per-capita ecological footprint is an indicator of the product of the Affluence and Technology terms, reported in global hectares (gha) required to produce the products and absorb the CO_2 associated with a particular lifestyle. In 2000, the global per-capita footprint available to all earth's inhabitants was ~2 gha. The United States was consuming about 12.2 gha/citizen, while China was consuming 1.8 gha/citizen. However, what would happen if China used current industrial age methods ('Technology' in the IPAT equation) to increase their consumption levels ('Affluence') to that of the U.S.? For China alone, this would exceed the entire annual regenerative capacity of the earth.

The next step would be to use causal loop diagrams to extend the visible spectrum of sustainable design opportunities (Fig. 8). These connections can be inferred or derived from data from websites like www.nationmaster.com. Again, it becomes obvious that the leverage for sustainable design lies in a combination of the social and design factors. This view of sustainability requires non-traditional, integrative thinking, which is a departure from the more traditional, reductionist analytical thinking. We should note that the *social* factors (such as *awareness*, or *motivation*) are not constrained by the laws of thermodynamics; noting that behavioral changes in the social system are free from any 'conservation laws' may be one of the keys to sustainable, systemic change.

The above example of China and the IPAT equation illustrates a less obvious and perhaps paradoxical implication of the embedded systems model: constraining the design with sustainability necessitates innovative thinking. Previous engineering designs, perhaps conceptually reflected in the 'Technology' term of the IPAT equation, have contributed to our current state of unsustainability. As shown in Fig. 2, the mental models that have produced our current situation prevent us from seeing other possibilities. Because sustainability requires new mental models, is opens up the possibility of new thinking.

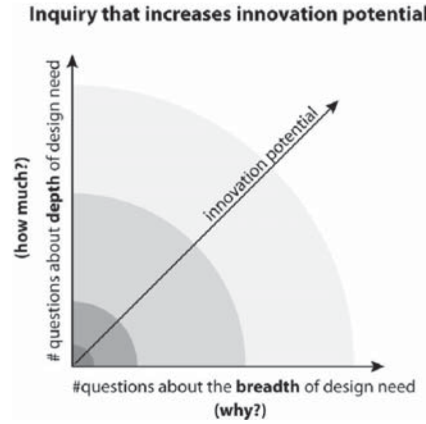

Fig. 9. Both lines of inquiry (depth & breadth) are required to increase the potential for innovation.

By definition, innovative, or 'new' thinking lies outside of current thinking. In other words, it is currently 'unknown.' We contend that accessing the unknown is a practice rooted in unconventional engineering attitudes and behaviors—a focus on exploring what one doesn't know, rather than asserting what one does know. Here, we suggest a process involving a re-conceptualization of the design need. One way in which this can happen is through a combination of two lines of inquiry, one that uncovers the depth of the needs and the other that exposes the breadth of the needs (Fig. 9). For example, one might assert they need a mechanism to transport mass. Questions around depth would presume that design solution (formal cause), mechanism to transport mass, and explore design criteria around it (How much? How far?). Questions around breadth would suspend the stated form and seek to uncover the purpose (final cause) to reveal opportunities for an entirely different form or design solution. This is another way of considering 'convergent' thinking and 'divergent' thinking, which has been shown to enhance design performance [33].

The goal is for the designer to have a more complete understanding of the design need that will reveal entirely new avenues of solutions. What is happening during the process of inquiry is that the designers are uncovering the mental models that initiated the design need and seeding the possibility for new mental models. For example, rather than focusing on the design of a car, one might focus on the underlying needs for transportation or even the needs to access goods and services in which case a more sustainable car is likely not the optimized solution [22]. Suspension of our existing mental models may be unlikely to occur in a design context that only includes engineers, simply because they may share the same mental models. That is, a design team of only engineers will decrease the likelihood that radical differences in mental models will exist or surface one anothers' hidden models. The probability drops even further if the design team is monocultural. Authentic engagement with those outside of our intellectual habitat, however, can provide the synergy necessary to extend our depth and breadth of inquiry and develop new mental models of ever-increasing complexity.

4.3 Situating the engineering design tools within the system

The embedded systems model enables one to conceptualize the production of toxins and waste for the life cycle within the economy (Fig. 10). Design for the life cycle often takes the form of minimizing a particular impact, such as embedded energy. However, situating the life cycle schematic within the embedded systems model makes clear that the 'surroundings' of the life cycle system is the environment, rather than some abstraction. All toxins released during the process are release into this environmental commons. With few exceptions, toxins released into the environment diminish the capacity of the environmental system to regenerate natural resources. They also negatively affect the numerator in Equation (1) through degrading health and welfare of the social system.

A powerful way to raise awareness is to direct students to sources of information regarding toxins release like the U.S. Environmental Protection Agency's Toxics Release Inventory [34]. They may not be aware of the fact that in the US alone, over 4 billion pounds of toxins are annually and *legally* released into the air, water and soil [34]. These represent voluntarily reported amounts in a country that constitutes less than 5% of the world's population and whose manufacturing sector comprises less than 10% of the total economic activity. It would be a valuable exercise for students to reflect on the global implication for countries that provide the world with its manufactured products. China (17% world population) and India (11% world population) have much larger manufacturing sectors and far fewer regulations. What naturally follows from this depiction is another thermodynamic reality: Systems which are sustainable cannot result in the accumulation of toxins into the environment, regardless of whether that environment is locally or globally shared [20].

The embedded systems model of reality with the life cycle superimposed on it as in Fig. 10 makes clear the thermodynamic reality of sustainability as a necessary design constraint. With a little deductive reasoning, students can draw on the embedded systems model to justify the second principle of green engineering: design for prevention, not treatment [22]. They will need to realize that treatment both requires resources from the environment and

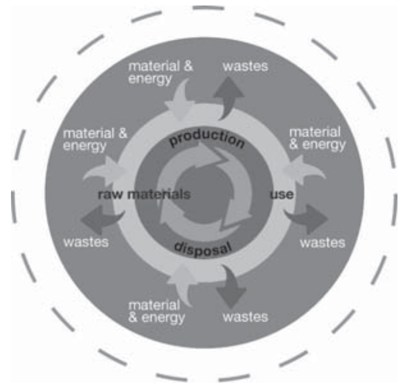

Fig. 10. Product life cycle superimposed on the embedded systems model. At all product stages, materials and energy are drawn from the environment and wastes are emitted to the environment.

emits waste to the environment, whereas designing for prevention simply requires new thinking.

5. STUDENT RESPONSES TO THE CONCEPTS

One of the authors (LV) taught a masters-level course using the concepts and activities described within this article. The context of the course was a public, primarily undergraduate university located in the western United States. There were eight students in the course, all of whom were male engineering students, taking the course as a technical elective. Three of the eight students were first-year masters-level graduate students and the rest were undergraduate seniors. The students met for four hours per week in two-hour blocks for ten weeks. They also took a laboratory that met for three-hours per week. The format of the course was active and dialectical. It was focused on enabling students to develop skills in three areas, with an emphasis on:

- Systems thinking and systems dynamic modeling (*understanding of dynamic complexity*);
- Design for the life cycle (*disciplinary mastery*);
- Metacognition and creativity (*capacity to innovate).*

Table 1 shows the course schedule of topics. Readings were from primary sources as much as possible. The group projects were of the students' own choosing, but had requirements of being large in scope and addressing a current campus systemic sustainable design challenge. Laboratory time was used to develop skill with dynamic simulation software, life cycle analysis software, and materials selection software. We also dedicated one laboratory session to mock climate negotiations using the climate simulation tool that was used in the December 2009 climate negotiations in Copenhagen [35].

At the end of the course, students were asked to provide any feedback on the course that they felt

Table 1. Schedule of course topics.

Weeks	Focus
1–4	Sustainability, systems thinking, systems dynamics
5–7	Life cycle design, assessment, sustainable design
8–10	Projects (1–3 people)
Final	Presentation of projects

would be helpful. All responses were collected so that the respondents remained anonymous. Students were informed that typed versions of the handwritten responses were given to the instructor after the course grades were assigned.

One of the themes that emerged in the responses was students' sense of the relevance of the ideas:

> [The course] was an invaluable class that profoundly validated and thoroughly investigated the need for systems thinking and design for sustainability for which our consumption driven culture is in such dire need . . . I . . . wish it were required for all engineering students . . . [Student 1]

> This course has opened my eyes completely to the real problems our planet is currently facing. I honestly believe that this could be a required course for all engineering students to take within the next few years . . . [Student 4]

> The broad and encompassing aspects of this class compliment the general curriculum of engineering very well . . . [Student 7]

Another theme that emerged was one of personal changes in viewpoint:

> I feel that this class was very insightful as far as pollution awareness goes. I was amazed by the amount of knowledge I gained when considering the [breadth] of topics we covered . . .There really is a lot of information to cover in this class and I feel that the way it was expressed allowed us to absorb it in a better fashion than traditional learning. You definitely changed us! [Student 5]

> [This] has been the most insightful, enjoyable class I have taken in my 6 years at [our university]. I have learned new ways of thinking in dynamic systems that have positively changed both my personal life and the way I view the world. [Student 2]

> . . . I think this courses' value lies in its thorough investigation of sustainability, forcing me to reassess my faddish notions of it . . . [Student 3]

> . . . Without a doubt, this class has shifted my way of thinking in terms of global issues, as well as my own participation in solving them. I have a renewed interest in finding a job in the sustainable/renewable energy sector. This course is highly valuable on a personal level. It both exposed me to the truths of our current situation as well as helped me to realize what mental models I rely on and how I can rethink them. [Student 6]

These responses are provided as a reference. Clearly many factors (e.g., elective course, pedagogical methods, pro-sustainability culture, small class size, previous experience with instructor, and a variety of unknown others) contributed to the way in which students responded to the ideas. However, the receptive nature of the responses is a hopeful sign that engineering students can embrace personal shifts in viewpoints, enjoy the process, and see the value in it.

6. CONCLUSIONS

The field of engineering is undergoing a paradigm shift from designing widgets to holistic design; this change necessitates a shift in the way that these designers are educated. We posit that there is a systemic relationship between the mental models of the designer, design process, the design itself and unintended consequences. If the mental models of the designer and design process are dissociated from the larger systems in which the design is embedded the result will be unsustainable. Widget-based design derives from mental models whose negative, global-scale consequences are no longer acceptable. When these same mental models are used to address questions of sustainability, they inevitably fail; they have in fact created our current situation and cannot change our current situation by additional application of them. To enable the possibility of sustainable design, we need to embrace a mental model that is inclusive of and accounts for the design as embedded within the closed thermodynamic system of the environment (biosphere) and a dynamic social system (anthroposphere). This also includes economic criteria. Such a process requires actively working with implicit and explicit mental models with an understanding of their systemic relationship to design consequences. This process, though individual and reflective is best taken up in a collaborative and collective fashion, involving design stakeholders who represent different viewpoints.

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APPENDIX

U.S. National Society of Professional Engineers Code of Ethics for Engineers

Preamble

Engineering is an important and learned profession. As members of this profession, engineers are expected to exhibit the highest standards of honesty and integrity. Engineering has a direct and vital impact on the quality of life for all people. Accordingly, the services provided by engineers require honesty, impartiality, fairness, and equity, and must be dedicated to the protection of the public health, safety, and welfare. Engineers must perform under a standard of professional behavior that requires adherence to the highest principles of ethical conduct.

I. Fundamental Canons

Engineers, in the fulfillment of their professional duties, shall:

1. Hold paramount the safety, health, and welfare of the public.
2. Perform services only in areas of their competence.
3. Issue public statements only in an objective and truthful manner.
4. Act for each employer or client as faithful agents or trustees.
5. Avoid deceptive acts.
6. Conduct themselves honorably, responsibly, ethically, and lawfully so as to enhance the honor, reputation, and usefulness of the profession.

Linda Vanasupa is a professor of materials engineering at the California Polytechnic State University in San Luis Obispo, California. She is the U.S. lead of a China-U.S. institute committed to collaborative design of sustainable rural communities. Her recent work is in the area of integrating issues of societal relevance into the engineering design process. She also serves as co-Director of the Center for Sustainability in Engineering at Cal Poly.

Roger Burton is a consultant who has spent the majority of the past 20 years in consulting with Fortune 20 companies for large, systemic transformation. His formal study is in western philosophy. He currently serves on the Board of Directors for the Society for Organizational Learning-China (Beijing, China).

Jonathan Stolk is an associate professor of mechanical engineering and materials science at Franklin W. Olin College of Engineering, where he offers project-based experiences in science, engineering, and design, and co-teaches a history-materials science course block that integrates technical learning with contextual analysis. His research interests include examining the role of faculty in promoting students' growth as self-directed learners, exploring the effects of disciplinary integration and project-based learning on students' motivation and competency development, and applying design thinking to engineering curriculum reform.

Julie Beth Zimmerman is an assistant professor jointly appointed to the Department of Chemical Engineering, Environmental Engineering Program and the School of Forestry and Environment. Dr. Zimmerman's research is aimed at designing and developing innovative science, technology, and policy to advance sustainability. She studies the effectiveness and impediments of current and potential policies developed to advance sustainability. Together, these efforts represent a systematic approach to addressing the challenges of sustainability.

Larry Leifer is a professor of mechanical engineering at Stanford University. Dr. Leifer's interests revolve around innovation and design thinking. He also serves as the Director of the Center for Design Research at Stanford.

Paul T. Anastas is professor in the Practice of Green Chemistry with appointments in the School of Forestry and Environmental Studies, Department of Chemistry, and Department of Chemical Engineering. In addition, Prof. Anastas serves as the Director of the Center for Green Chemistry and Green Engineering at Yale. Dr. Anastas has published widely on topics of science through sustainability, such as the books Benign by Design, Designing Safer Polymers, Green Engineering, and his seminal work with co-author John Warner, Green Chemistry: Theory and Practice.