AC 2007-2422: IMPLEMENTING SUSTAINABILITY IN THE ENGINEERING CURRICULUM: REALIZING THE ASCE BODY OF KNOWLEDGE

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Implementing Sustainability in the Engineering Curriculum: Realizing the ASCE Body of Knowledge

Abstract

ASCE has committed the profession to sustainability for at least a decade. The implied educational imperative is for a broader and deeper preparation of new engineers, and at the same time, of the practicing profession. The ASCE committee working on the second edition of the Civil Engineering Body of Knowledge has embraced sustainability as an independent technical outcome; and has set out specific levels of cognitive achievement required of all engineers prior to licensure. Herein, we discuss the elements of a university program including the sustainable use of natural resources, sustainable infrastructure, sustainable production of goods and services, and a research agenda. We also comment on the implied experiential component required beyond the university.

Introduction

Sustainability is cited as the top systems integration problem facing engineering today and into the future[i]. This is corroborated by the Joint Charter[ii] among the American Society of Civil Engineers (ASCE), the Canadian Society of Civil Engineers (CSCE), and the Institution of Civil Engineers (ICE), wherein professional responsibility is asserted for realizing sustainable civil society across all peoples and through time. Codes of Engineering Ethics from ASCE and the National Society of Professional Engineers (NSPE) reinforce this responsibility. Further, the recently-announced aspirational vision of the civil engineering profession[vii] embodies this goal. Broadly consistent with all previous statements about the purpose of engineering, these recent documents extend beyond technological competence to professional responsibility or *outcomes*; and the outcomes include human rights, the environment, and the stewardship of natural resources as the fundamental basis of technological progress.

Profound adjustment to the reality of the commitment is required now on the part of today's educators and the rising generation of engineers. Not only must engineers be capable of recognizing sustainable works and services; they must also claim responsibility for implementing it, and seek social acceptance of that role. The latter requires the delegation of substantive authority in limited spheres of operation, and a means of licensing to recognize capable individuals. This is a tall order and requires thorough supplements and refinements in education in order to impact the profession. Not only must the education be placed on an expanding base of sound learning; it must also produce substantive communication among engineers, other professionals, and the service population in all of its complexity.

The efforts at updating the Civil Engineering (CE) Body of Knowledge (BOK)[iii] required for licensure as a professional engineer, have embraced sustainability as a fundamental outcome. This implies that *every* civil engineer must have mastered this *minimum* BOK acquired through demonstrated and approved channels prior to licensure.

This paper addresses the curricular implementation of this BOK outcome. Included are expansions of the 'general education' base in four areas: math, science, social science, and humanities. This is necessary in order to firmly ground the professional in the multifaceted bases of sustainability, and to connect him/her broadly to the service population, the details of social implementation, and the roles of engineering and the other professions.

Beyond this base, a substantive focus is needed on

- Natural resources—the foundation of all engineering activity
- Infrastructure and the built environment
- Innovation and the importance of discovery

The BOK goes further in discussing achievements beyond licensure that is essential if the performance of the profession is to be judged. This is especially crucial in sustainability, given the long time constants required for realization.

Lastly, these ideas are not unique to civil engineering and incorporation of these items is recommended for all engineering curricula that serve civilian (as distinct from military) interests.

Background: Civil Engineering and Sustainability

Civil engineering developed in the 19th century with a distinctive focus on civilian infrastructure and the technological support of civil society. It continued to affirm this mission throughout the 20th century and beyond. Necessarily, technology continues to evolve and problems mirror society in their increasing scale and complexity. The globalization of civil society has brought a parallel globalization of civil engineering concerns and its practitioners. A primary dimension of this concern is *sustainability*.

Unquestionably, global scenarios are infused with technology, the natural resource base that sustains civil society, and the natural and the built environment. We are faced with the depletion of fossil resources; the management of new energy sources including the nuclear fuel cycle; the bioengineering of photosynthesis for fuel, food, and drugs; the maintenance of agricultural productivity; the increasing exploitation of the oceans; the human right to water; nuclear chemistry; and more. Anthropogenic influences are clearly visible in the global ecosystem: species extinction; exhaustion of depletable resources; geopolitical conflict over ownership of renewable resources; and degradation of the planetary commons (atmosphere, oceans). Civil engineering cannot by itself "solve" these problems; yet it must embrace a proactive, professional stance and contribute an accompanying distinctive competence toward their resolution.

The ASCE definition was adopted in November 1996:

> ***Sustainable Development** is the challenge of meeting human needs for natural resources, industrial products, energy, food, transportation, shelter, and effective waste management while conserving and protecting environmental quality and the natural resource base essential for future development.*

In 1996 the ASCE Code of Ethics recognized this as an ethical obligation of the profession. Fundamental Canon 1 asserts

Engineers shall hold paramount the safety, health and welfare of the public and shall strive to comply with the principles of sustainable development in the performance of their professional duties.

In 2006, NSPE adopted a comparable ethics statement. In 2004, ASCE incorporated these statements into Policy Statement 418 that affirmed the role of the profession in addressing and securing sustainability:

The American Society of Civil Engineers (ASCE) recognizes the leadership role of engineers in sustainable development, and their responsibility to provide quality and innovation in addressing the challenges of sustainability.

In June 2002, the "Dialog on the Engineers' Role in Sustainable Development—Johannesburg and Beyond" (NAE 2002) committed its signatories (AAES, AIChE, ASME, NAE, NSPE) to the declaration:

Creating a sustainable world that provides a safe, secure, healthy life for all peoples is a priority for the US engineering community. … Engineers must deliver solutions that are technically viable, commercially feasible and, environmentally and socially sustainable.

Partly in response, the ASCE Committee on Sustainability published *Sustainable Engineering Practice: An Introduction* in 2004. This report

…is intended to be a 'primer' on sustainability that … can inspire and encourage engineers to pursue and integrate sustainable engineering into their work…

and describes the state-of-the-art at the time of its publication. A great deal of practical material is assembled in this document.

The NAE convened important symposia in 2004[iv] and 2005[v] to address engineering and engineering education reflective of contemporary challenges. Sustainability was clearly emphasized as part of this:

An even greater, and ultimately more important, systems problem than homeland security is the 'sustainable development' of human societies on this system of ultimate complexity and fragility we call Earth. (Vest.[vi])

ASCE convened a summit of leaders of the profession in 2006. The vision expressed at the summit reinforces the NAE and related themes[vii]:

Entrusted by society to create a sustainable world and enhance the global quality of life, civil engineers serve competently, collaboratively, and ethically as master:

- *planners, designers, constructors, and operators of society's economic and social engine, the built environment;*
- *stewards of the natural environment and its resources;*
- *innovators and integrators of ideas and technology across the public, private, and academic sectors;*
- *managers of risk and uncertainty caused by natural events, accidents, and other threats; and*
- *leaders in discussions and decisions shaping public environmental and infrastructure policy.*

This vision is broadly assertive of aspirations to sustainable engineering, stewardship of the natural resources and the environment, and the fostering and integration of innovation in service of these ends—all in the basic overriding context of service to people through civilian engineering. Equally important is the intention expressed in the opening phrase to earn and retain the social trust necessary in these matters.

Clearly, ASCE is committing the profession to the *delivery* of sustainable engineering. Knowledge of the principles of sustainability, as they affect engineering practice, is therefore required of civil engineers.

Interdisciplinarity

There are social, economic, and physical aspects of sustainability, affecting technology, natural resources, and the environment. A broad, integrative understanding of all of these aspects is necessary. Beyond that, *special competence* is required in the scientific understanding of natural resources and the environment, which are the foundation of all human activity; and the integration of this knowledge into practical designs that support and sustain human development.

It goes without saying that the actual life of an engineered work may extend well beyond the design life; and the actual nature of the outcomes, more comprehensive that initially intended. Sustainable engineering must consider this longer and wider framework in evaluating actions.

Individual projects make separate claims on the *collective* future but they cannot be considered in isolation. A commitment to sustainable engineering implies a commitment across the profession to the resolution of the *cumulative* effects of individual projects. In an era of rapid global expansion of civil works, ignoring their cumulative effects can lead to overall failure.

The Body of Knowledge

ASCE has defined the competence of civil engineers in terms of a Body of Knowledge (BOK). The first version appeared in 2004[viii] and focused on the *outcomes*—the knowledge, skills, and attitudes—required for entry into professional practice. The outcomes reflect contemporary and emerging challenges.

Sustainability is expressly recognized as a new outcome amongst the technical outcomes in the emerging second edition of the BOK (BOK2). Consistent with the "Raise the Bar" effort across CE education, this describes a new competence *required of all candidates for licensure*.

In addressing educational outcomes, the BOK2 effort uses the taxonomy of Bloom et al.[ix] which has the following six levels of achievement in ascending order: *knowledge, comprehension, application, analysis, synthesis,* and *evaluation*. Sustainability is expected to be leaned up to level 3 (application) through formal education, and level 4 (synthesis) is expected to be learned through pre-licensure experience. Figure 1 shows a summary of BOK outcomes.

	Foundation	1 Knowledge	2 Comprehension	3 Application	4 Analysis	5 Synthesis	6 Evaluation
1	Mathematics	B	B	B			
2	Physics	B	B	B			
3	Chemistry	B	B	B			
4	Breadth in basic science	B	B	B			
5	Humanities	B	B	B			
6	Social sciences	B	B	B			

	Technical	1 Knowledge	2 Comprehension	3 Application	4 Analysis	5 Synthesis	6 Evaluation
5	Mechanics of Physical Systems	B	B	B	B		
6	Behavior of Materials	B	B	B			
7	Breadth in civil engineering areas	B	B	B	B		
8	Engineering tools	B	B	B	M/30		
9	Engineering problem solving	B	B	B	M/30		
10	Design	B	B	B	B	B	E
11	Experiments	B	B	B	B	M/30	
12	Contemporary & emerging issues	B	B	B	E		
13	Risk/uncertainty	B	B	B	E		
14	Sustainability	B	B	B	E		
15	Project management	B	B	B	E		
16	Technical specialization	B	M/30	M/30	M/30	M/30	E

	Professional	1 Knowledge	2 Comprehension	3 Application	4 Analysis	5 Synthesis	6 Evaluation
17	Communication	B	B	B	B	E	
18	History and heritage	B	B				
19	Globalization	B	B	B	B		
20	Prof. & ethical responsibility	B	B	B	B	E	E
21	Public policy	B	B	E			
22	Business & public administration	B	B	E			
23	Teamwork	B	B	B	E		
24	Leadership	B	B	B	E		
25	Life-long learning	B	B	B	E	E	
26	Attitudes	B	B	E			

Key:	
B	Portion of Body of Knowledge fulfilled through the Bachelor's degree.
M/30	Portion of Body of Knowledge fulfilled through the Master's degree or the equivalent.
E	Portion of Body of Knowledge fulfilled through pre-licensure experience.

Figure 1. BOK2 outcomes and achievement levels. The method of achievement is indicated in color.

What is Sustainable Engineering?

The ASCE definition of *sustainable development* cited above was adopted in November 1996 by the ASCE Board of Direction, and has been recognized since then in the ASCE Code of Ethics[1]. In the BOK2 this is adapted without substantive change:

> ***Sustainability*** *is the ability to meet human needs for natural resources, industrial products, energy, food, transportation, shelter, and effective waste management while conserving and protecting environmental quality and the natural resource base essential for the future.*

Sustainable engineering meets these human needs. The BOK2 requirement for all Civil Engineers, as currently drafted is:

> ***The 21st century civil engineer must demonstrate*** *an ability to evaluate the sustainability of engineered systems and services, and of the natural resource base on which they depend; and to design accordingly.*

Specific levels of achievement at the culmination of the BS and subsequently at the completion of pre-licensure experience are listed in the Rubric shown in Table 2. Implied further is a hierarchy of achievement, beginning with the earliest university descriptions, proceeding through licensure and culminating in profession-wide performance.

Fundamental is the notion of supporting and sustaining human development and achievement, through technology in three areas:

- Sustaining the availability and productivity of natural resources, the ultimate base of civil society
- Sustaining civil infrastructure, the engineered environment
- Sustaining the environment generally, the human habitat

There are other critical dimensions of sustainability, notably the economic, social, and political aspects of civil life. Implied in effective engineering is the right deployment of technology toward human problems that arise in these social contexts; and the search for technological breakthroughs inspired by these problems.

Clearly, contemporary civilization is perfused with technological features, challenges, concerns. The depletion of fossil resources; the management of new energy sources including the nuclear fuel cycle; the bioengineering of photosynthesis for fuel, food, and drugs; the maintenance of agricultural productivity; the increasing exploitation of the oceans; the human right to water; nuclear chemistry; and more. And clearly at the close of the 20th Century, antrhopogenic influences are visible in the global ecosystem: species extinction, exhaustion of depletable Natural Resources, geopolitical conflict over ownership of renewables (rivers), degradation of planetary commons (atmospheric CO2, oceanic habitat). Those trends demand engineering attention.

Specifics of the sustainability outcome appear in Tables 1 and 2 at the end of this paper. The **Outcome** statement (Table 2) summarizes the BOK2 expectation through licensure; the **Rubric** (Table 1) shows the full longitudinal profile for an individual starting at the collegiate level. Both use the Bloom cognitive achievement levels as a metric.

Educational Program

Sustainability makes Claims on the Foundation

The sustainability outcome is not independent of other BOK outcomes. In particular, it rests on a foundation comprising the four classical categories of humanities, social science, mathematics, and the sciences. Historically, this foundation has been explicit about math and science, with the other two categories unconstrained. Sustainability makes new claims on the math and science, adding to the burden there. It also makes fresh claims on the formerly unconstrained humanities and social sciences.

Mathematics is a classic foundational topic. Quantitative, analytical approaches are implied in the description of sustainability as in other areas of engineering. Special requirements arise in the command of basic probability, statistics, and stochastic dynamics in order to handle data interpretation, risk, and the necessity of stochastic simulation in dealing scientifically with ecological and social phenomena.

Similarly in the *sciences*, the foundational need is classic. Sustainable engineering requires a scientific approach, one based on observation, deduction, and theory. Earth science and biology must be added to the traditional requirements of physics and chemistry. These are necessary to support studies of natural resources and the environment.

In the *humanities*, a proper professional preparation begins with developing an understanding of human beings: their aspirations and possibilities; their social nature; and the common good and how it is served (or thwarted!) by technology.[x] Study in the humanities must inform us about human aspirations, achievements, and failures, in human terms, how to hear and express them, and where responsibility lies in achievement. Simply stated, it is in the study of the humanities, alongside other citizens and pre-professionals, that the object of engineering–facilitating authentic human value–is examined and challenged in terms of authentic human service.

In the *social sciences*, the professional must command institutions that deliver services. A healthy understanding of economic and political mechanisms is necessary. To properly utilize these mechanisms, it is essential to distinguish three primary types of institutions–government, corporate, and professional–and the opportunities involved in each distinct form (see e.g. Lynch[xi]; Friedson[xii]). In particular, an understanding is needed of public goods, market imperfections, externalities, natural monopoly and monopoly regulation, consumers' and producers' surplus, *etc*. Engineers need to be prepared to act within imperfect, real institutions; and to understand how to construct 'governance structures', what they can achieve, and where their weaknesses lie. There are excellent current treatments of public goods (e.g., Musgrave[xiii], Kaul et al[xiv,xv])

These claims on the humanities and social sciences foundation are novel in engineering education. They are implied in the inclusion of explicit general outcomes in the BOK and discussed at greater length by Evans et al[xvi]. An excellent case study is the Universal Declaration of Human Rights, and the obstacles to its realization now, roughly 60 years after its enactment. Clearly, sustainability was not in the WWII lexicon. What is the burden implied today? Are there explicit rights implied in technological services, for example the Human Right to Water[xvii]? And what will help or hinder the realization of the Millennium Development Goals in the context of sustainability?

Engineers must be broadly educated in each of these foundational areas, or else they will fall behind their own aspirations. All these foundational 'subjects' need to deliver proper support for the sustainability outcome. The foundation is broad: Rhodes[xviii] discussed Sustainability as "the ultimate Liberal Art"; and Vest[xix] is explicit on the importance of the humanities and social sciences in support of the "twenty-first-century view of engineering systems, which surely are not based solely on physics and chemistry."

Some Specific Educational Priorities in Sustainability

A broad, integrative understanding of sustainability is necessary at the foundational level. Beyond this, *special competence* is required of engineers in three specific areas that deserve careful attention:

- Natural resources and the environment
- Infrastructure
- The research frontier

Together these cover the human habitat–both natural and constructed–and the knowledge necessary for it to function and evolve sustainably.

Natural Resources and the Environment

It is incumbent on engineers who seek to support civil society, to understand and coordinate the natural resource base. Resources are simultaneously the source of all material productivity, and the environment that sustains all living things. A holistic view indicates a closed system in which natural resources both sustain human activity, and are sustained by it.

A theoretical description is necessary, one that integrates the diverse phenomena and is capable of relating to observation. Such a general description needs at least three diverse elements:

- *Ownership*: who and/or what organizations have legal or other entitlement to the state and use of the resource?
- *Value*: what are the descriptors of scarcity and of value–whether in-use, or in-situ?
- *Physics*[xx]: what are the relevant physical phenomena, what are the "laws of motion" governing them, and how are the related state variables observed?

While the third item is classic in the sciences, the relevant phenomena are spread across a variety of scientific disciplines including biology and earth sciences. The first two are classically the realm of the humanities and social sciences. *An integrating framework is needed*; one that sees immediately the importance of the claims made on the foundational preparation (above). The special value added by engineering science will lie in the quantitative integration—scientific in its approach to data and phenomena, and prescriptive in its approach to doing things. This is not unlike many other areas of engineering sciences; the proper formulation will employ differential equations, stochastic simulation, linear and integer programming, queuing theory, optimization theory, and competitive decision-making. Successful deployment of these theoretical constructs provides an integration of natural resources within the engineering sciences.

Within this general framework, one can distinguish several cases.

***Nonrenewable Sterile Resources*:** The classic case is that of mineral wealth. Here one is confronted with private ownership linked to land ownership. The dynamic is one of discovery, invention of valuable use, depletion, escalating costs of production, substitution, and ultimately the closeout of the resource following 'economic' exhaustion. Complicating the picture is the competition among suppliers, the relative availability of information about competitors, nationalization of private assets, and necessary investments in production, processing, transportation, and end-use capital. The most common contemporary example is perhaps petroleum. Clearly all of the above are operative in a complex but global market influenced by geopolitics. Sterile resources are dealth with extensively in resource economics (e.g., *e.g.* Conrad[xxi] Clark, [xxii] Nehrer[xxiii]).

Renewable Living Resources: In this category we include fisheries and forests, and living populations in general. All share the possibility of multiple steady states, where harvesting balances growth. The search for good sustainable states involves the search for: a) control of the harvesting; b) monitoring mechanisms of the resource itself; c) a theory which explains natural variability; and d) a theory of social value. The renewable resource can be exhausted and this is its inevitable limit when harvesting rates exceed renewal rates. Essentially, resource renewability is not exogenous (as in water), but endogenous, requiring a living inventory for its generation. Marine resources are classically described in these terms. They are elevated in importance since the Law of the Sea has given exclusive economic jurisdiction over the continental shelf to maritime nations; hence public ownership extends over what was previously an international commons. Texts available in this area are common in the fisheries arena: Clark[xxiv]; Mangel[xxv]; Hillborn, Walters[xxvi]; Getz and Haight[xxvii]; Caswell[xxviii]. The *Earthtrends* database[xxix] of the World Resources Institute has historically been very useful.

Renewable Sterile Resources: Water is the standard example of a renewable sterile resouce. It is routinely distilled from the ocean and deposited on land, distributed via hydrologic processes, and recycled. The geophysical occurrence is certainly stochastic, and elements of hydrology have commonly been embedded in engineering studies focused on water infrastructure and regional development. Within the framework here, we have a scarce, essential, and economically valuable resource, a natural distribution system, and the opportunity to affect distribution via infrastructure. Ownership is political, as rivers commonly mark, and aquifers underlie, national borders. Legal distinctions of appropriative versus riparian systems, upstream, downstream, and historical uses are important, and international law is less developed that that of individual states. Economic uses include such regional essentials as navigation, irrigation, and power, and urban necessities including water supply and sanitation have advanced to the point of being declared human rights[xxx, xxxi]. Further, pollution prevention and/or remediation, is costly yet essentially unavoidable. (In this respect, water shares some features with the degradable category below.) There is no question about value, although the various uses serve diverse interests and all share a "natural monopoly" status. Steady states are possible, and indeed one must think in terms of steady uses supplied by a stochastic availability, seek infrastructure which smooths that stochasticity, and respect the constancy of many uses. There have been excellent texts in this area (e.g. Loucks[xxxii]). Recent attention to sustainability has been clearly focused (Loucks [xxxiii]**;** Bogardi et al[xxxiv]) There is an excellent recent compilation of data by Shiklomanov *et al* [xxxv]; and contemporary issues are covered biennially in the reports from Gleick[xxxvi].

Degradable Resources: This final category contains many examples of anthopogenic degradation, and examples of pollution and pollutant dispersion come to mind. Agricultural land may be one of the prime candidates. If this resource is conceived as the acreage of arable land, then one can conceive of it as finite, requiring other resources (e.g., water, fertilizer) and requiring significant economic infrastructure as in the case of nonrenewable sterile resouces. Ownership is historically private, and the public goods nature of nutrition and public health are dependent historically on competitive private supply from this resource. Sustainable steady states are possible, although chemical and biotic impoverishment requires economic management. However, these processes operates on slower time scales than those related to production, and so the tendency to treat a degradable resource like an exhaustible one, or an extinctable one, is clearly embedded in the unregulated economy. Historically, land use has been a leading concern in development studies, and arable land, land tenure, and water rights comprise a significant arena of activity. Complicating the contemporary situation is an expanded interest in agricultural fuels. This is adding additional pressure for fuel production to already-intense pressure for food, fiber, and habitat conservation uses.

Curriculum Issues: Examples of integrated treatments of sustainability concepts, for an engineering audience, are hard to locate but are encouraged (e.g. Lynch[xxxvii]). The use of a consistent mathematical nomenclature has been a stumbling block here—one needs to work across many separate disciplines. Contributions to this synthesis are greatly needed.

There are two educational modes for the teaching of this material. In the first mode, create a specific integrating course around natural resource sustainability as sketched here. An alternative is to use the same integrated natural resource material as examples in other courses in applied mathematics (differential equations, matrix algebra, control theory, optimization, and stochastic dynamics). This approach loses the coherence of the resource theme as a component of sustainability, instead adopting with a "natural resources across the curriculum" theme.

Infrastructure

One of the defining characteristics of civil infrastructure systems is their long half-life *vis a vis* systems designed for other applications. For example railroads versus automobiles versus personal computers. A second important characteristic is that infrastructure systems and buildings occupy space on our planet for long periods of time—many generations in some cases—and often outlive the technology originally designed for the space. Many of the canals in the U.S. were outdated by the railroad before they were even completed and some have become important recreational corridors today. Other modes of transportation have replaced passenger railroads and their right-of-ways are now abandoned or in urban areas share the land with other infrastructure networks.

Another important characteristic of infrastructure is its visibility. Abandoned infrastructure and buildings are very visible to the public and may be seen as engineering failures that do not improve the image of engineering as a profession, despite the fact that these structures may have represented cutting-edge technology when they were built. The fact is that the design did not consider the full life cycle—the day when the structure would no longer be needed and would have to be deconstructed, and the area returned to its natural state. Is it not reasonable to expect sustainable infrastructure systems to be designed considering their full life cycle?

Many buildings constructed before the age of industrialization were retrofitted with central heating systems, and will be retrofitted again at some point to systems that do not depend on fossil fuels. It is difficult to predict when, but not to predict that wide spread use of fossil fuels for heating buildings will pass. Sustainable infrastructure systems must be designed for recycling and reuse or deconstruction. The intergenerational principle of sustainability requires this long-term view.

It is conceivable that in the future highways as we know them will no longer be needed to transport people and goods. What would we do with these system? Transportation corridors could be integral to some other infrastructure network. Many roads in this country began as trails for native Americans, were upgraded to wagon trails, and today underlie or parallel interstate highways. In urban areas, major road corridors often include other major infrastructure systems such as water, wastewater, energy and communications. A failure in one system can cause a cascading failure in a co-located but unrelated system. Bordogna emphasized the need for the future civil engineer to be a master systems integrator and Vest[vi] emphasizes the importance of systems thinking in achieving sustainability.

Infrastructure is increasingly being computerized to enhance performance. Building control systems have been in widespread use for more than 10 years and in the future will be enabled by Web-based technologies. Surface transportation systems are being computerized to relieve congestions and reduce air pollution. Smart buildings have the potential to greatly improve energy efficiency in operation. Online systems can help consumers manage energy use in their buildings.[xxxviii] In buildings, security can be integrated with other building functions such as HVAC.[xxxix,xl] Building IT systems are now beginning to merge with other building systems.[xli]

Sustainable infrastructure systems have economic, social and environmental aspects. The role of the civil engineer and other built-environment professionals will vary during the life cycle from conception to return of the land to its natural or near natural state. In some cases the civil engineer will be the lead professional, and in other cases an important member of the team. In all cases the civil engineer must be an advocate for ensuring the sustainability of the overall system.

Engineering practice is always evolving. Following Koehn, good engineering practice as exhibited in for example infrastructure is judged against the best state-of-the-art at the time of design and construction—Kohen's "sota." When we review infrastructure from another time, it is fair to ask if it met or exceeded the sota of the time. The professional societies play an important role as keepers of the sota and in encouraging its improvement. ASCE's mission is "To provide essential value to our members, their careers, our partners and the public by developing leadership, advancing technology, advocating lifelong learning, and promoting the profession."[xlii] Advancing technology would certainly include technology related to intelligent transportation systems (ITS).

Cities are important and their systems are not only vital but they are increasingly complex and interconnected. Security has been added as an additional systems constraint. ASCE has launched a program entitled "Practice, Education, and Research for Sustainable Infrastructure" or PERSI (ASCE, 2006). In addition to principles, engineers and other decision makers for infrastructure need authoritative practices, such as criteria, guidelines, manuals, standards and regulations, to guide, support and implement their decisions.

Urban transportation systems have an enormous impact on the urban quality of life. When we talk about transportation, the issue may not be only about what we traditionally think of as transportation. Questions such as "Is mobility a basic human right?" also have to be considered. We must move products and services from producers to consumers and we must provide mobility for people, e.g., for the poor to get to work. The poor in urban urban areas are often completely dependent on public transportation for mobility.

The American History Museum presents civil engineering in the context of transportation infrastructure in its America on the Move exhibit.[xliii] Congestion in downtown Washington, D.C. is not too bad but getting downtown is another story. In 1958 Bello said about the interstate highway system that "Many local governments saw the interstate program as an answer to urban transportation problems. New roads, they believed, would increase economic growth. But roads in urban areas sometimes ran up against community resistance. A few were never built; some were reshaped by community input." In the 1960's the solution to congestion in Washington was a proposed interstate through downtown Washington. This proposal was defeated in 1972 and never built. The resistance to this solution raised serious social issues that should have been addressed in the design.

What role could ITS play in a more sustainable transportation system? The European Union (EU) has incorporated ITS into its Common Transport Policy across all modes and is working at creating a single market for ITS services. The Community Guidelines for the development of the Trans-European Network for Transport (TEN-T) are promoting the use of information technologies throughout the transportation system. The TEN-T guidelines recognize that the development of ITS can make a major contribution to increasing road transport efficiency, safety and sustainability.[xliv] However, the new EU transportation strategy is apparently in conflict with the new EU policy on sustainable development.[xlv] Sustainable infrastructure requires an integrative approach. Canada's ITS plan explicitly links ITS to sustainability.[xlvi]

According to the U.S. EPA some of the advantages of ITS are a smoother traffic flow with less delay from signals, incidents, and traffic queues. Environmental benefits include emissions reduction, increased roadway capacity, and decreased fuel consumption.[xlvii]

Civil engineering education is challenged to "addresses environmental, culture, economic, and social impacts of engineering on society and the concept of sustainable development" in an exciting unified way. Civil engineers must be prepared to take a lead role in ensuring that our infrastructure systems transition to sustainable infrastructure systems.

Some useful references on sustainable infrastructure are:

- ASCE Code of Ethics <http://www.asce.org/inside/codeofethics.cfm>
- ASCE Committee on Sustainability <http://www.asce.org/instfound/techcomm_cs.cfm>
- ASCE Policy 418 The Role of the Civil Engineering in Sustainable Development <http://www.asce.org/pressroom/news/policy_details.cfm?hdlid=60>
- ASCE Report on Forum on Technical Opportunities for Sustainable Infrastructure, ASCE Committee on Sustainability, Approved June 3, 2005 <http://www.asce.org/files/pdf/instfound/june05report.pdf>
- Editors of Fortune (1957 Exploding Metropolis, Garden City, NY, Double Day Anchor.
- Jacobs, J (2004). *Dark Age Ahead.* Random House, New York.

The Research Frontier

No one would assert that at present we know how to achieve a steady, productive relationship with nature. Thus we are in a transient stage where knowledge and hence technology must be advancing toward more sustainable practices. This research frontier is probably the greatest scientific challenge we face and the professional burden is to channel it toward new possibilities. Otherwise, the very notion of civil engineering is folly.

The classic notion of the substitution doctrine is relevant here: as we exhaust one way of living, we invent another. The ultimate sustainable resource is human knowledge, and so we can ask, "Are we learning how to do without, faster that we are exhausting present possibilities?" The error commonly made is to leave this to an invisible hand, which justifies inaction. There is no theory to justify exclusive reliance on an invisible hand. Since the substitution involves the unknown–of unknown knowledge for today's unsustainable practices–such a reliance would at best be tautological. ("What will happen, will happen".)

Clearly there is a great challenge facing us. During the present generation, per capita material throughput can be expected to rise to Western European standards, perhaps a factor of five beyond the status quo; and our footprint is already beyond one. [xlviii] Population expansion may add another factor of two. Hence the aggregate material reliance, given today's technology and legitimate human aspirations, can grow by a factor of 10. We can in a draconian manner, abandon legitimate aspirations, or we can find the factor of 10 in every industrial process and product. The latter is the research frontier.

We depend, critically on the research frontier. There is little to say here, except that the ultimate, undiminishable common good is human creativity and solidarity. The critical ingredients may well be faith in the human spirit, coupled with announcing the problem. The most important words may well be the analog of the now-famous utterance, "Houston, we have a problem", coupled with a resolve to inspire many to perform. The professional aspiration announced in the ASCE vision, implies a burden to focus this frontier on sustainability issues in a major way. Research priorities will need to reflect this and is implied in the professional vision of engineering service to society. A suggested list of research programs that spans all engineering would focus on enduring human concerns:

- Productivity, organization, and management
- Natural resources and the environment
- Infrastructure
- Security
- Health

These would be closely coupled to professional preparation. The overlap with sustainability of civil engineering systems as presented here, is clear. Each of these is infused with technology, yet none is uniquely 'technical'. Each requires the multi-disciplined approach characteristic of the NAE and ASCE visions.

Beyond Academia: The Need for an Experiential Program

The discussion above focused on the preparation of *new* engineers who are cognizant of sustainability principles and practices. The residence time in the profession is perhaps 30 years. Rapid change in professional performance, on the scale demanded by sustainability, cannot be expected to occur by relying solely on this formal education. Simultaneous injection of sustainability expertise is needed in the professional years following formal education.

This theme is reflected in the BOK2 outcomes. The sustainability outcome is to be fulfilled partly through the BS degree (Bloom's level 3), and further (Bloom's level 4) in the pre-licensure, experiential phase of practical experience. From a purely educational point of view, it is not possible to deal realistically with the project, infrastructure, and natural resource time-scales involved, and with the synergy among projects and clients, in the academic setting.

Further, with sustainability concerns today largely originating at the client interface, reliance on the post-BS experience phase is particularly appropriate. Practical performance is required there, in advance of having a firm Body of Knowledge in place. Sustainable professional performance cannot await the completion of individual lifecycle timescales. Here we are seeing the full problem, where listening to client needs, interpreting them into technical terms, finding sustainable solutions, and explaining them to the public, must all come together.

Elsewhere[xlix] we suggest general strategies for an experiential learning program, based on extant models of architecture, medicine, and Canadian engineering. We refer the reader to this discussion as it seems particularly relevant to the fulfillment of the sustainability outcome. In particular, this is likely to require renewed cooperative efforts among academics and professionals in practice, and some considerable experimentation with organizational models.

Sustainable performance will involve the whole profession. A commitment is needed to all aspects, all levels, all forms of specialists and generalists. It is not unlike other more conventional engineering outcomes; but a minimum competence in sustainability is clearly required of all engineers in order to earn the social trust and role aspired to in the vision.

Generalization

It is impossible to extract these ideas from their originating home within civil engineering. We assert, however, their essential alignment with engineering generally. We see the BOK effort as emblematic of a broad and necessary movement toward directing technology toward civilian service. There is little value in restricting these ideas to mechanical, electrical, chemical, nuclear, etc. phenomena *per se*. The idea of professional service to civil society transcends these categories.

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Table 1. RUBRIC for new Outcome: Sustainability.
A longitudinal profile of an individual professional's development.

Level I Knowledge (B)	**Define** key aspects of sustainability relative to engineering phenomena, society at large and its dependence on natural resources, and the ethical obligation of the professional engineer. Rationale: Proactive integration of diverse considerations is implied at the point where an engineering solution is proposed and evaluated. Implied is an ability to conceive of the full lifecycle of an engineering project, and a comprehensive set of outcomes, including effects on the environment, the natural resource base, the conditions at project termination, and the appropriateness of the project itself and how it serves Public Interest.
Level II Comprehension (B)	**Explain** key properties of sustainability, and their scientific bases, as they pertain to engineered works and services. Rationale: This is the natural extension of Level I. A blend of theory and experiment is likely in applying ideas to engineered systems. A scientific explanation is necessary, especially relative to Natural Resources and to the natural and built environment, where established scientific descriptions are available.
Level III Application (B)	**Apply** the principles of sustainability to the design of traditional and emergent engineering systems. Rationale: This is the natural extension of Level II. Graduate must be capable of applying ideas to real engineering works; and of utilizing general information available within the profession.
Level IV Analysis (Experience Pre-Licensure)	**Analyze** systems of engineered works, whether traditional or emergent, for sustainable performance. Rationale: This is a systems-level integration of cumulative and synergistic effects of works with respect the sustainability of the composite outcome. Implied is the ability to propose and compare alternatives in an analytic framework.
Level V Synthesis (Experience Post-Licensure)	**Design** a complex system, process, or project to perform sustainably; **Develop** new, more sustainable technology; C**reate** new knowledge or forms of analysis in areas where scientific knowledge limits sustainable design. Rationale: This is either professional-strength design, or research. The latter can have varying amounts of scientific overlap.
Level VI Evaluation (Experience Post-Licensure)	**Evaluate** the sustainability of complex systems, whether proposed or existing. Rationale: This is referring to the ability to inspire and evaluate the work of teams engaged synergistically. Included is the ability to quantify the value of research in sustainable engineering.

Table 2. Outcome: Sustainability

Overview: The 21st Century Civil Engineer must demonstrate an ability to analyze the sustainability of engineered systems, and of the natural resource base on which they depend; and to design accordingly.

ASCE embraced sustainability as an ethical obligation in 1996[l], and Policy Statement 418[li] points to the leadership role that civil engineers must play in sustainable development. The 2006 ASCE Summit[lii] called for renewed professional commitment to stewardship of natural resources and the environment. Knowledge of the principles of sustainability[liii], and their expression in engineering practice, is required of all civil engineers.

There are social, economic, and physical[liv] aspects of sustainability. The latter includes both natural resources and the environment. Technology affects all three and a broad, integrative understanding is necessary in support of the public interest. Beyond that, *special competence* is required in the scientific understanding of natural resources and the environment, which are the foundation of all human activity; and the integration of this knowledge into practical designs that support and sustain human development. Vest[lv] referred to this as the primary systems problem facing the 21st century engineer.

The actual life of an engineered work may extend well beyond the design life; and the actual outcomes may be more comprehensive than initial design intentions. The burden of the engineer is to address sustainability in this longer and wider framework.

Individual projects make separate claims on the collective future; ultimately they cannot be considered in isolation. A commitment to sustainable engineering implies a commitment, across the profession, to the resolution of the cumulative effects of individual projects. Ignoring cumulative effects can lead to overall failure. This concern must be expressed by the profession generally, and affect its interaction with civil society.

B: Upon graduation from a baccalaureate program, an individual must be able to *apply* the principles of sustainability[liii] to the design of traditional and emergent systems (Level **3**)**.** Implied is mastery of a) the scientific understanding of natural resources and the environment, and b) the ethical obligation to relate these sustainably to the public interest. This mastery must rest on a wide educational base[lvi], supporting 2-way communication with the service population about the desirability of sustainability and its scientific and technical possibilities.

E: Upon completion of pre-licensure experience and before entry into the practice of civil engineering at the professional level, an individual must be able to *analyze* systems of engineered works, whether traditional or emergent, for sustainable performance (Level **4**). Analysis assumes a scientific, systems-level integration and evaluation of social, economic, and physical factors – the three aspects of sustainability. Achievement at this level requires the "B" achievement described above to be advanced in practice to the analysis level, through structured experience and in synergy with other real works, built or planned. Successful progression of cognitive development in this experiential phase must be demonstrable.

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