Int. J. Engng Ed. Vol. 9, No. 1, pp. 51–55, 1993
Printed in Great Britain.

0742–0269/91 $3.00+0.00

Systemic Change for Engineering Education: Integrated Trends in the United States

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The US national workshops, reports and papers of the past decade suggesting paradigm shifts in engineering education reveal a common theme, namely that engineering is an integrative process and thus engineering education, particularly at the baccalaureate level, should be designed toward this end.

Enveloping a change in intellectual culture, the roots of contemporary collegiate education in the United States are noted, the current emphasis on reductionism in relation to integration is discussed, the desire of society for a more complete engineer is accepted, and a holistic approach to baccalaureate education, in which process and knowledge are woven throughout the curriculum, is suggested.

At the graduate level, the trend is toward two focused tracks:

(1) an integrative program leading to a practice-oriented, technology-based Master's degree;
(2) The extant research-oriented, discovery-based Doctoral degree.

Variations include integrated management and technology programs at the Master's level and Doctoral research dissertations at the interfaces of seemingly disparate disciplines.

At both undergraduate and graduate levels there is an increasing partnership between academe and industry fostered and catalyzed by both state and federal governments. The nexus of this partnership is intellectual, but a strategic objective is to bring to bear on innovation and wealth creation, the integrated talents, interests and resources of US society.

HISTORICAL BACKGROUND

AT LEAST two founders of the United States called for engineering talent early on. In a paper published in 1749 [1], Benjamin Franklin suggested that the curriculum for educating young people in the developing colonies of North America should include teaching of 'Mechanicks . . . to be informed of the Principles of that Art by which weak Men perform such Wonders, Labour is saved, Manufactures expedited . . .' He also urged that learning be pursued so as to balance useful knowledge with the liberal arts, and with the specific intent of serving mankind. He further urged that such intent should indeed be the 'great Aim and End of all Learning.'

Just prior to the writing of the Declaration of Independence, the sense of possible separation from the importation of manufactured goods prompted concern among colonial leaders that indigenous manufacturing would need to be quickly developed along with the public works necessary for commerce flow. In 1776, the year the Declaration of Independence was promulgated, Adam Smith, in his economic treatise *The Wealth of Nations* specified government responsibility for creating the physical infrastructure to allow low inventory factories in a market economy. With these allusions to engineering matters, General George Washington issued an order establishing an engineering school as a corps within the Continental Army to develop engineers for the construction of public works. When he became President, it was no surprise when the Congress of the newly created United States established, in 1794, an engineering school at West Point in the State of New York, later to become part of the US Military Academy established there in 1802. In 1817, Colonel Thayer, Superintendent of West Point, began organizing a formal civil engineering curriculum there modelled on France's Ecole Polytechnic [2].

In 1821, what is believed to be the first engineering course in a United States' civilian institution was announced in the catalogue of Norwich Academy in the State of Vermont. Although Rensselaer Polytechnic Institute (RPI) was founded later (1824 in the State of New York) than Norwich, it granted the nation's first formal civilian engineering degrees in 1835 (Norwich's first engineering degrees were awarded in 1837). It is interesting to note that RPI was founded by a private citizen for 'sons and daughters of mechanics' to learn the 'application of experimental chemistry, philosophy, natural history to agriculture, domestic economy, the arts and manufactures.'

According to eighteenth-century colonial belief, engineering should include a blend of the arts, and the creation of artifacts, and systems in service to society. In this way an engineering education in the United States laid the foundation for a kind of liberality in the undergraduate programs that subsequently developed in the latter half of the twentieth century.

Between 1840 and 1860, fewer than ten additional engineering schools were established, but following the Morrill Land Grant Law passed in 1862 by Congress, the number of new engineering schools really began to grow. This law allocated land to individual states for founding colleges with emphasis on agriculture and the mechanic arts, the purpose being to enhance commerce and strengthen the economy.

The growth of engineering schools in the United States from the mid-nineteenth century onwards generally followed the pattern set by technological progress, growth of manufacturing in industry, and the application of machinery and science to agriculture. Civil engineering developed mainly from the need to build a physical infrastructure of roads, waterways, and sanitary facilities for effective commerce flow in a frontier nation; mechanical engineering developed during the mid-1800s in response to the enhancement of human muscle power by steam engines; the first electrical engineering courses were begun in the late 1880s following the invention of dynamos, the electric light bulb (1882), and the consequent societal demand for electrification of cities; the first chemical engineering curricula were established in the early 1890s when oil was recognized as an attractive power source; industrial engineering was born in response to growth of large-scale production systems. The twentieth century saw the birth of high-speed, large-scale transportation vehicles and networks, the advent of high-speed, large-scale communications and computing, the evolution of large-scale materials processing, and more recently, the joining of engineering and medicine . . . and so on.

All this activity has led to today's US engineering education enterprise of about 300 engineering schools enrolling annually about 340 000 full-time baccalaureate students (40 000 part-time), 40 000 full-time Master's degree students and 30 000 full-time Doctoral degree students, with 45 000 part-time graduate students totalling the Master's and Ph.D. [3]. Graduation is of the order of 60 000 baccalaureates, 27 000 Master's degree students, and 6000 Ph.D.s each year [4].

Over a century and a half of existence, engineering education in the United States has changed from a tinkering activity to standardized rules of design, to a carefully intellectualized analytic science base. While the more recent change to a scientific base has served us well, there is growing belief in the United States that something remains missing.

MAKING THINGS—CONCURRENT INTEGRATION

The determinants of economic well-being have changed radically during the past half-century, prompted by fine tuning the industrial revolution concurrently with the advent of universally expansive high-speed computing. In the past, certainly through World War II, these determinants included garnering large land masses containing rich lodes of natural resources, substantial population size for an enabling workforce, military power for security, and large amounts of capital. Now, however, with the onset of increasingly fast-paced technological change, a coalescing global marketplace, and almost instantaneous wide-bandwith communication, the determinants of economic well-being look quite different: quick application of technology, diligent investment in workforce education, maintenance of a stable political environment for a functional marketplace, establishment of a reliable physical infrastructure for facile commerce flow, and development of public policy that facilitates capital investment.

Because of this shift, the engineer's task in society takes on a much expanded dimension. For example [5], mid-twentieth century manufacturing demanded a choice of two of three facets of manufacturing: making a product well, making it quickly, and making it inexpensively. As we enter the next century, it is necessary not only to satisfy all three of these but additionally two more: making it safely and making it environmentally benign. A new paradigm for making things thus develops: applying intelligence, or cognitive expertise (human or otherwise), across all dimensions of the manufacturing process; integrating across all dimensions concurrently; and diffusing or deploying technology perpetually into the societal infrastructure. This expanded responsibility suggests that tomorrow's engineer will have to be functionally literate across a number of disciplines, not merely well-educated in one. Further, an individual engineer's decision-making will have to be much more value laden than value free.

Put another way, engineering now assumes a tighter partnership on the wealth-creation team of an increasingly idea-driven society. As one model, the engineering process can be considered as one of five elements which must be integrated concurrently (instead of serially as has been in the past) in order to innovate effectively and create shared wealth with regard for environmental fragility. These elements are: scientific inquiry, engineering integration, available technology, economic context, and public policy. Scientific inquiry to create knowledge is a critical element of the process. It is an analytic, reductionist activity digging deeply into the secrets of the universe to discover what is not yet known; good science leads to fresh ideas. The essence of engineering is the process of integrating knowledge to some purpose [6] and is focused on the synthesis and implementation of ideas. It is an activity centered on connecting pieces of knowledge and technology to synthesize new products, systems, and services of high quality. Engineers are party to the creation of knowledge, and in universities and industrial research laboratories many engineers pursue new knowledge with focused goals in mind. But the functional core of the engineering process, the expectation society has for the engineering profession, is the 'putting together of things'.

Technology, the third element in this model of wealth creation, is the 'armoury' available to do things with, the devices, processes, systems, ideas, crafts, and artifacts available at any moment in history from which fresh products, systems, and services are created. As an example, physically small, highly component-dense electronic systems were not possible with early vacuum tube technology; semiconductor technology had to develop first from scientific inquiry.

Of course, the market forces constantly at work help determine societal need, and from this the public policy that can either nurture or mitigate against the entire process. This parameter of innovation and wealth creation, along with the context of economic operation (the fourth and fifth elements in the model), form an envelope in which science, engineering, and technology mix well or not so well. The main idea here is that innovation and wealth creation are nurtured or stymied by our ability to communicate among these basic societal elements and to work them together. In this process, the engineer, if properly educated with integration as a reason for being, will have the functional background to effect some leadership in nurturing the entire interactive process of wealth creation to a better end. Simply put, engineers today must be educated to do no less than be proactive partners in the day-to-day process of bettering society's standard of living.

THE CONTEXT OF ENGINEERING EDUCATION FOR THE TWENTY-FIRST CENTURY

Based on the preceding notions and studies, engineering educators in the United States are seeking fresh ways to match the traditional academic departmental structure, based on disciplines, with the emerging technologies which motivate the industrial enterprise and lie at the base of wealth creation. They pursue this agenda in partnership with industry and government by seeking new modes and norms, not merely by replicating their experiences but by innovating from them. In a formal effort to understand and institutionalize this trend, a number of national workshops, staffed by distinguished engineering educators, industrialists, and government officials were conducted during the past decade [7]. The reports and papers emanating from these efforts suggest paradigm shifts in engineering-education synergistic with the model of innovation and wealth creation suggested above; examples are given in references 7–11. These all reveal a common theme: engineering is an integrative process and thus engineering education, particularly at the baccalaureate level, should be designed toward this end.

Present undergraduate curricula in the United States require students to learn in unconnected pieces, separate courses whose relationship to each other and to the engineering process are not explained until late in a baccalaureate education, if ever. Education in engineering thus proceeds 'bottom up.' For example, in non-unified chunks, a student has to study mathematics and science before being 'allowed' to frame an engineering problem, let alone proceed to build anything. This now classical educational system is displayed in Fig. 1 where its tone of channelling students through limiting filters is indicated schematically.*

Further, an engineering education is usually described in terms of a curriculum designed to present to students the set of topics engineers 'need to know', leading to the conclusion that an engineering education is simply a collection of

* The abbreviation 'HSS' means Humanities and Social Sciences.

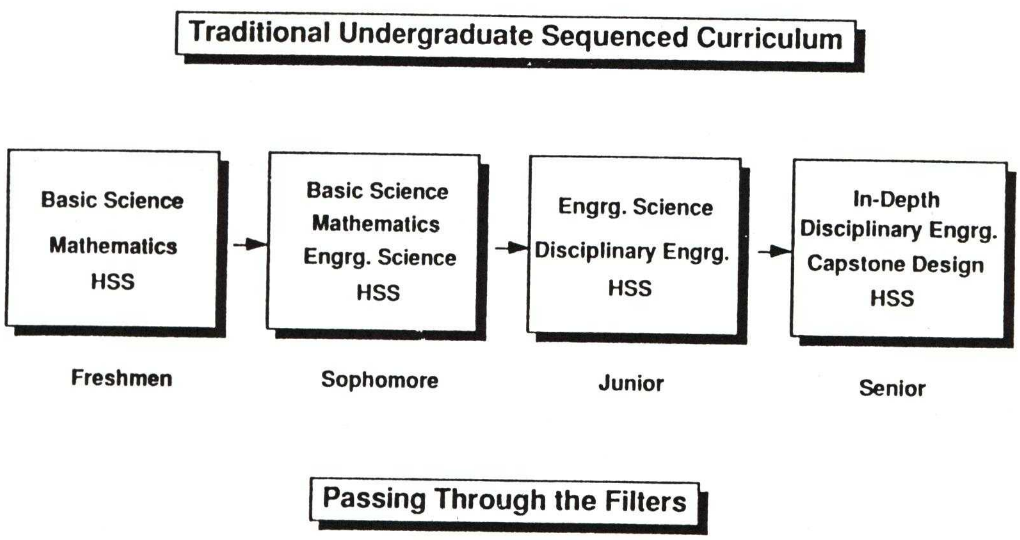

Fig. 1. The traditional undergraduate sequenced curriculum.

Table 1. A balanced engineering education

Vertical (in-depth) thinking	Lateral (functional) thinking
Develop order	Correlate chaos
Solve problems	Formulate problems
Develop ideas	Implement ideas
Understand certainty	Handle ambiguity
Abstract learning	Experiential learning
Reductionism	Integration
Analysis	Synthesis
Research	Design/process/manufacture
Independence	Teamwork
Techno-scientific base	Societal context
Engineering science	Functional core of engineering

courses. The content of the courses may be valuable but this view of engineering education appears to ignore the need for connections and for integration, which many believe should be at the core of an undergraduate engineering education.

In terms of the present curriculum structure, many of the undergraduate courses are described as fundamental. In terms of science, mathematics, and engineering science skills needed, this definition is viable, but what are the basic constructs of the engineering process itself? What does the phrase 'engineering is an integrative process' mean? Table 1 identifies the components of a balanced or holistic baccalaureate engineering education [7, 12]. The columnar arrangement and component juxtapositions highlight what is often perceived as the antithesis of one to the other. With some introspection we would generally recognize that the historical changes which brought greater emphasis to a science base in engineering education over the last half century, has focused our curricula to include those components on the left, but often has done so to the exclusion of those on the right. If we are to achieve balance we must redefine the inclusiveness of the engineering educational enterprise, for intellectual and functional completeness as well as intellectual rigor.

How do we educate our students to understand that creation of knowledge and its integration go hand-in-hand as a framework for organized cultural, intellectual, political, and social evolution? The overall objective is to develop functional literacy or lateral depth across elements of Table 1. The concept of lateral depth in this attempt to develop integrative capabilities, is in sharp contrast to the in-depth or vertical depth effort needed for good research. For an integrative task, lateral depth is concerned not only with investigating a number

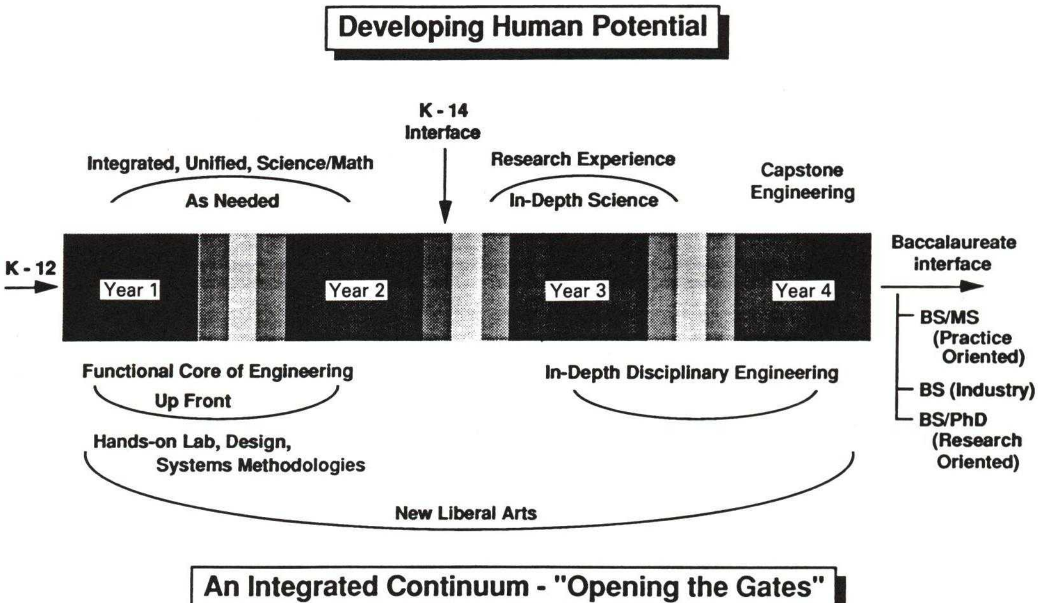

Fig. 2. An integrative approach to undergraduate education.

of areas in depth, but also developing the connections among them. Both are needed in tackling open-ended problems and opportunities, the kinds of activities engineers usually face as professionals.

This context suggests that emphasis in engineering education programs should shift from emphasis on course content, with its consequent filtering of students as shown in Fig. 1, to a more comprehensive view focusing on the development of human resources and the broader educational experience in which the individual parts are connected and integrated, as illustrated in Fig. 2. Using these precepts as a base, the task before us is to develop more provocative approaches to engineering education. Thus, a vision of engineering education for the twenty-first century can be based on the notion that the engineer's essential role in organized society is an integrative one, i.e., emphasizing 'construction of the whole.' The primary goals of an engineering education should therefore be to develop, as in individualized a way as possible, the following capabilities in each student [13]:

Integrative capability. Recognition of engineering as an integrative process in which analysis and synthesis are supported with sensitivity to societal need and environmental fragility.
Analysis capability. The critical thinking that underlies problem definition (modelling, simulation, experiment, optimization) and derives from an in-depth understanding of the physical, life, and mathematical sciences, as well as the humanities and social sciences.
Innovation and synthesis capability. The creation and elegant implementation of useful systems and products, including their design and manufacture.
Contextual understanding capability. Appreciation of the economic, industrial, and international environment in which engineering is practiced and the ability to provide societal leadership effectively.

With these new thoughts focused at the undergraduate level, Fig. 2 suggests that at the graduate level, the trend is toward two focused tracks.

(1) an integrative program leading to a practice-oriented technology-based Master's degree;
(2) the extant research-oriented, discovery-based Doctoral degree.

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