

# Design, Systems, and Engineering Education

CLIVE L. DYM

Department of Engineering, Harvey Mudd College, Claremont, CA 91711–5990, USA.

E-mail: [clive\\_dym@hmc.edu](mailto:clive_dym@hmc.edu)

*In the context of providing opening themes for Mudd Design Workshop IV, Designing Engineering Education, this paper suggests that calls for change in engineering education could benefit from the application of precepts from design theory and from systems analysis. Design precepts could help frame objectives for the engineering education enterprise and identify functions that would achieve those objectives, and it could provide metrics against which the achievement of objectives can be assessed. Systems precepts could help identify and articulate how the elements of the engineering education enterprise are related and how they interact, an understanding of which would greatly facilitate identifying processes by which change could be brought to engineering education.*

## INTRODUCTION

THE MODERN, *science-based engineering curriculum* is often viewed as originating with the Grinter report [1, 2] that reflected in part the thinking embodied in the famed Vannevar Bush Report [3]—which argued for greater public investment in science because of the impact of such ‘scientific’ advances as radar and operations research during World War II—and in part, as detailed by Seely [4], by the culmination of the efforts of several engineering educators who had benefited from the European, more theoretical approach to engineering. (Seely [4] quotes Walker [5] as writing, ‘They taught us elegant theory: vector diagrams . . . , hyperbolic functions . . . , and even triple integrals.’) The rapid and widespread acceptance of the Grinter report was accelerated by the Soviet Union’s 1957 launch of Sputnik. Now, some five decades later, with recognizably similar curricula across a broad spectrum of institutions, American engineering schools, generally acknowledge some common concerns about their programs, among which are:

- the content and presentation of the curriculum;
- the effectiveness of learning by students;
- the retention of those students in the classroom;
- the adequacy of programmatic funding at their own institutions; and
- the graduation of an adequately-sized, appropriately-educated workforce of engineering professionals to maintain and enhance America’s technologically-rich, service-oriented economy and lifestyle.

These concerns and more have been raised in a consistent stream of calls for change in and reform

of the engineering education enterprise (see, for examples [6–22] and the reference lists in [20, 22]). These calls have varied in focus, aiming at curriculum and course content [6–12], student learning issues [9, 15, 16], industry involvement [10, 13], and still others at the institutional structure of the enterprise itself [14–22].

In the face of this constant chorus, have things changed much since the 1950s? As one data point, compare changes in the curricula of two private, undergraduate colleges of some repute, The Cooper Union and Harvey Mudd College (Figs 1 and 2). These were chosen as exemplars in part because the author has ties to both, having received his B.C.E. from Cooper in 1962 and having taught at Mudd since 1991. In addition, both schools are well known and invariably rank at or near the top of lists of ‘best’ programs (e.g., ranked second and third in the 2003 *U.S. News* ranking of ‘Best Undergraduate Engineering Programs’ [23].) Evidence of great change does not leap off the pages of Figs 1 and 2. Certainly the total number of required credits has changed, as have the number of required—versus elective—courses. There have been some changes in the flavors of each program, perhaps most notably the inclusion of instruction in computing and of first-year design courses. And, in the case of Mudd, there is the three-semester ‘capstone’ Engineering Clinic program founded in 1965 in which students work on real, externally-sponsored design and development projects [24–26]. (The Appendix contains a brief overview of Mudd’s curriculum.)

On the other hand, most of the first two years of the engineering curriculum continue to be devoted to foundational courses in mathematics, physics, and chemistry, as well as courses in the humanities and social sciences. Thus, almost all of the first year and most of the second of an engineering major is still spent with faculty in non-engineering

\* Accepted 3 November 2003.

departments. The last two years are devoted largely to engineering courses, with streams of varying depth in the humanities and social sciences and a virtual absence of courses in the basic sciences or mathematics. In addition to Mudd's Engineering Clinic, the Cooper and Mudd programs also differ significantly in the upper division because Cooper offers degrees in chemical, civil, electrical

and mechanical engineering, while Mudd offers only a single, broad, unspecialized degree. Nevertheless, notwithstanding these differences, the larger point about relative change over the last four decades remains the same for both schools: the basic structure of the engineering curriculum is largely unchanged.

Assuming that these two curricula and their

1962			2002		
<b>1st Year</b>			<b>1st Year</b>		
Chemistry I, II	F	S	Chemistry I, II	F	S
Mathematics I, II	5.5	5.5	Mathematics I, II, III	3	4.5
Physics I	4	4	Physics I	6	4
English I, II		5	Studies in Lit. I, II	3	3
Engrng. Graphics	3	2	Engrng. Design	3	
Surveying	4.5		Comput. Prog. for Engrs.	3	
Physical Education		5		2	
	1	1			
<b>2nd Year</b>			<b>2nd Year</b>		
Mathematics III, IV	5	3	Mathematics IV, V, VI	4	3
Physics II, III	6.5	4	Physics II, III	5.5	4
Statics & Dynamics I, II	2	2	Engrng., Solid Mechanics	3	3
Civil Engrng. Problems		4.5	Materials Science	3	
Economics	3		Elect. Engrng.		3
Public Speaking	2		Engrng./Sci. Elect. I		3
Civilization I		3	Modern Society I, II	3	3
<b>3rd Year</b>			<b>3rd Year</b>		
Elect. Circuits & Machs.	3		Environ. Sys. Engrng.	4.5	
Mechs. of Materials I, II	4	4.5	Engrng./Sci. Elect. I		3
Fluid Mechanics I	4.5		Fluids, Water Res. Engrng.	3	4.5
Structures I, II	3.5	4.5	Structures I, II	4.5	3
Thermodynamics		3	Thermodynamics	3	
Soil Mechanics		3.5	Soil Mechanics		4.5
Civilization II, III	3	3	Hum. & Soc. Sci. Elect. I, II	3	3
<b>4th Year</b>			<b>4th Year</b>		
Highway Engrng.	2		Structures III	3	
Fluid Mechanics II	3		Urban Transport. Planning	3	
Civil Engrng Design I, II	4.5	4.5	Civil Engrng. Design I, II	3	3
Civil Engrng Projects I, II	1	1	Civil Engrng Projects		2
Atom. & Nuclear Physics	3		Engrng./Sci. Elect. II, III, IV	3	6
Civilization IV	3		Hum. & Soc. Sci. Elect. III, IV	3	3
Sanitary Engrng.		3.5			
Structures III		3			
Social Philosophy		3			
<b>TOTAL CREDITS (1962)</b>	<b>143.5</b>		<b>TOTAL CREDITS (2002)</b>	<b>135</b>	

Fig. 1. Cooper Union's B.C.E. curricula for 1962 and 2002.

changes over time are reasonably representative of engineering programs generally, what can we learn from this brief analysis? Has the engineering curriculum 'stood the test of time'? Are engineering schools successfully meeting most of society's expectations? Or, has the engineering enterprise 'been resistant to change'? If change is resisted, why? Further, if change is resisted, can that resistance be overcome?

The fourth biennial Mudd Design Workshop (MDW) was convened under its title, *Designing Engineering Education*, to deal with just such questions. It is a theme that emerged during the closing luncheon of MDW III, *Social Dimensions of Engineering Design*, during which its participants articulated a desire to see wider and deeper changes in engineering education and, even, in college and university education in general [27, 28].

1962			2002		
1st Year	F	S	1st Year	F	S
Chemistry I, II	4	4	Chemistry I, II	4	4
Mathematics I, II	4	4	Mathematics I, II	4	3
Physics I, II	4	4	Physics I, II	2	4
English I, II	3	3	Hum. & Soc. Sci. I, II	4	3
Engrng. Problems III, IV	2	2	Intro. Engrng. Design		3
			Computer Science	3	
2nd Year			2nd Year		
Chemistry III, IV	3	4	Mathematics III, IV	3	3
Mathematics III, IV	3	3	Physics III	4	
Physics III, IV	4	4	Hum. & Soc. Sci. III, IV	3	3
Humanities I, II	3	3	Biology or Free Elective	3	3
Social Sciences I, II	3	3	Intro. Engrng. Systems	3	
			Experimental. Engrng.		3
			Design Rep. & Real.		1
			Continuum Mechanics		3
3rd Year			3rd Year		
Thermodynamics	4		Chem. & Thermal Processes	3	
Elec. Engrng. I, II	4	3	Electron. & Magnet. Devices	2	
Mechanics		3	Computer Engrng.		3
Technical Electives I, II	3	3	Adv. Engrng. Systems I, II	3	3
Mathematics V, VI	3	3	Engrng. Seminar I, II	0	0
Humanities III, IV	3	3	Engrng. Clinic I		3
Social Sciences III, IV	3	3	Technical Elective I		3
			Hum. & Soc. Sci. V, VI, VII	6	3
4th Year			4th Year		
Sol. State Mol. Engrng.	3		Materials Engrng.		3
Engrng. Lab. I, II	2	2	Engrng. Seminar III, IV	0	0
Engrng. Des. & Anal. I, II	4	4	Engrng. Clinic II, III	3	3
Technical Electives III, IV	3	3	Technical Elective II, III	3	3
Humanities V, VI	3	3	Hum. & Soc. Sci. VIII-XII	6	9
Social Sciences V, VI	3	3	Integrative Experience		3
TOTAL CREDITS (1962)	138		TOTAL CREDITS (2002)	128	

Fig. 2. Harvey Mudd College's B.S.E. curricula for 1962 and 2002.

### WHY CHANGE? IS ENGINEERING EDUCATION BROKEN?

It can be safely and fairly said that much that is good about modern life stems from advances made by engineers. Further, the United States is the source of much, even most of the technological advances that drive the global economy and provides at least the potential for improving the quality of life across the globe. The argument can certainly be made that engineering is not broken and, as we all say, 'If it ain't broke, don't fix it'.

On the other hand, as noted above, there are critics aplenty, and they find fault with curricula, with learning, with graduates, and even with the operational style and focus of many of our leading engineering schools. So the debate is joined. Yet, I would argue, it is much less the case that 'engineering education is broke(n)' than, almost certainly (and more productively), 'Can we do things still better?'

What does it mean to 'do things still better'? And, if we knew how to 'do things still better', how would we implement the changes needed to actually make things still better? I want to suggest that answers to these *What?* and *How?* questions could be greatly improved if some basic precepts from *design theory* and from *systems analysis* are brought into play as answers are sought.

### DESIGN AND ENGINEERING EDUCATION

To paraphrase a wonderful observation about *knowledge* offered by Stefik and Conway [29],

The engineering education system is an artifact, worthy of design.

This paraphrase is not meant to suggest that the engineering educational enterprise was created randomly, thoughtlessly, or without a great deal of painstaking intellectual effort. Rather, it is meant to suggest exercising the fundamental steps in the design of artifacts—both physical and meta-physical—could help make critiques of the engineering education system more constructive and corresponding analyses more useful. Further, the point is not to create a brand new design for the engineering education system in its own right, but to provide a structured approach to informed questioning of the current enterprise.

Some of the basic steps in a design-based approach are [30]:

- eliciting and refining properly drawn *objectives*;
- articulating appropriate and realistic *constraints*;
- deriving the *functions* that must be performed in order to realize the desired objectives within the extant constraints; and
- detailing the *metrics* against which the achievement of the objectives can be measured and assessed.

One important question addressed only implicitly

in this abbreviated list is, *Whose objectives are being elicited?* The answer(s) to this question is/are crucial because the objectives will almost surely vary with the role of the respondent. *Students* want a good educational experience leading to good jobs or graduate school; *professors* want to do research; *employers* want young, newly-graduated hires with twenty-five years of experience, ready to do any job competently and productively; *trustees* want to fulfill the fiduciary responsibility of ensuring that the college remains financially sound; *presidents* want their university to be exciting to potential donors; and *alumni* want the program to be just as demanding as it was in 'the good old days'. Are these objectives commensurate? Do they conflict? Are there still more players (or constituents, customers or stakeholders) with their own particular objectives? And which players are entitled to set goals for any particular engineering program?

Two published sets of objectives are worth mentioning in this context. The Boeing Company has long advocated a set of attributes that their ideal engineering graduate would have [31], and these can be taken as an appropriate set of objectives for an engineering curriculum or program. ABET, through its EC 2000 program, has advanced its own set of objectives for engineering curricula that are being widely used to assess the outcomes of engineering curricula [32]. It is perhaps too soon to say how effective the new ABET objectives are, how well they can be used to derive functions, or—and this may be the most crucial aspect—what are the appropriate metrics.

Objectives also provide a useful way to frame questions about an existing design or curriculum. For example, engineering curricula are very highly structured, locked in to long, serial course sequences. What, and whose, objectives are being served by this aspect of the curriculum? Does it reflect a faculty intent to organize a building-block approach to learning 'everything an engineer should know'? Does it reflect an implicit demand by an accreditation agency to advance its own goals? Does it reflect a student's cynical objective to leap as easily as possible over the seemingly disjoint curricula hurdles?

Similarly with constraints, although we typically think of constraints in a financial context: parents are generally constrained in their ability to pay tuition; donors are constrained by their own resources, as well as by their interest in the institution; and colleges are constrained from meeting a variety of needs by their endowments or by their appropriations.

Yet constraints are often intellectual or meta-physical, and they may result from objectives set in the distant past. As noted earlier, engineering curricula were institutionalized within an engineering-*science* model of engineering, and they are delivered within academic cultures that generally conform to the scientific research enterprise that has characterized university and college education in this country since the Vannevar Bush

Report. Further, the constraint is most rigidly felt during the first two years of the engineering curriculum, when some of the most important components of the curriculum are delivered by departments of mathematics, physics and chemistry. This a severe constraint whose justifications and costs need closer examination, especially since, this is, arguably, the time in the curriculum that students want to identify with engineering.

The benefits of a design-based approach lie most clearly in the underlying questions, e.g., Why are we doing this?, and Do we have to do it just this way?, and How are we going to do it? And, for the sake of completeness, let me propose one new curricular objective and one revised constraint [9]:

**New objective.** Design should be the *cornerstone* of the engineering curriculum, rather than just being its ‘capstone’. One consequence is that engineering science is taught in order to support students’ ability to design.

**Revised constraint.** Engineering curricula should be stated as a sum of a set of skills that students are expected to master and a set of *experiences* in which they will participate (i.e., an engineering program =  $\sum$  (skills + experiences), rather than as lists of subjects that students must know and courses they must take. The lists of skills and experiences derive from identifying what an engineering graduate must be able to *do*, rather than specifying what must be known.

## THE ENGINEERING EDUCATION SYSTEM

Even with the guidance of design methodology, identifying the right questions or *issues* and proposing practicable improvements or *fixes* for engineering education is hard because, as so artfully depicted by Magee [33], talking about engineering education means talking about the *engineering education system*—a system with an abundant number of *elements* or *degrees of freedom*:

- *institutions* (e.g., colleges, universities, departments, accreditation agencies, high schools, graduate schools, governments, government agencies, professional societies, companies, industries);
- *constituents* or *customers* (e.g., students, faculty, administrators, alumni, research sponsors, donors, politicians, and so on);
- *processes* (e.g., pedagogical, tenure and promotion, fiscal and accounting, accreditation, communication and outreach, and so on); and
- *sources of funding* (e.g., tuition, legislative appropriations, endowment income, research grants, foundations, donors, etc.).

As begun to be evident in the discussion of objectives and constraints in the previous section, given the number and variety of the elements involved (i.e., of constituents, institutions, processes and sources of funds), it would seem incredulous to claim complete understanding, miraculous to expect major change. Simply put,

the system’s numerous elements or degrees of freedom are multi-faceted and strongly coupled, both within and across layers or types; and its modeling and understanding require both *inter-disciplinary* and *multi-disciplinary* analysis.

Having said this, is it worthwhile to do a *system-of-systems analysis* of the engineering education system? It will no doubt be complicated. Many of the elements identified just above are themselves systems or sub-systems: certainly the institutions can be so regarded, and likely their processes as well. At perhaps at lower levels of abstraction, so too the constituents and sources of funding. However, it is desirable—perhaps even essential—if systemic change is the goal [34].

Without such analysis, how do we justify proposed systemic changes? That is, how do we identify meaningful objectives, their appropriate systemic levels, and the corresponding metrics against which performance can be assessed?

Without such analysis, how can we delineate a realistic path by which proposed changes can be realized? Where are the constraints, the rewards and inducements, the levers of power? What can be done nationally? What can be done only locally? What roles do the various institutions play? How can these institutions be persuaded, motivated or forced to respond? All of these questions and more—many of them ‘political’ and so perhaps unresponsive to straightforward logic—must be answered to define the road to reform, and can be answered through systemic analysis.

The argument has been made that engineering education should include such systems-of-systems analysis skills [8]. There seems little doubt that the same skills can be used to bring change to the engineering education system itself [34].

## CONCLUSIONS

I hope that the foregoing remarks have not painted too bleak a picture of the difficulty of achieving change. The challenge is real, but not insurmountable. We need not make all engineering curricula look so much alike. We should accept—and even take pride in—the fact that they might differ, even markedly. The objectives of all engineering programs won’t be the same, and certainly their constraints and their own elements or degrees of freedom will also differ. Nevertheless, there are enough similarities that an informed common inquiry can benefit all. The shift in ABET criteria toward more outcomes-oriented assessments is a welcome step in this direction—and may well provide a further and powerful prod to change [20, 35], although there remains concern that the procedures by which outcomes are assessed might be over-prescribed, leading to new versions of institutional stultification.

For myself, first of all, I strongly believe in the theme that Simon first enunciated in 1969 [36], namely, that *design is the distinguishing mark of the*

*engineering profession*. Second, I strongly urge a review of the balance between depth and breadth in an engineering program: our undergraduate curricula need greater technical breadth to achieve a better understanding of *systems* and *systems of systems* [8]. Third, I believe that a good engineering education is about *process*, about learning *how to think like an engineer*; it is much more than a prescription of content. In my ideal world, the undergraduate degree would be awarded after a broad, unspecialized education in the *art and science of engineering*: specialization would be left to the master's degree. (I find it wryly ironic that some still urge more specialization in the undergraduate program [37], while major professional societies want the masters degree be the educational requirement for admission to professional status, so that the baccalaureate can be more general [38].)

Now, finally, it is up to the entire engineering profession—including practitioners and employers, as well as educators and students—to *team together* to identify and work toward more universal aspirations with fewer restrictions. And speaking most directly to my faculty colleagues, we have to work as a team. In the same way that undergraduate engineering students are expected to

learn teamwork after their K-12 experiences of being graded as individuals [9], we must work together with our several constituents to make our undergraduate programs less faculty-centric and more student- and world-centric. The suggestions offered herein—to use precepts of design and of systems analysis to support our work—are intended to help move the team toward a better understanding of the engineering education system, and toward better support for our aspirations.

*Acknowledgements*—I am very pleased to acknowledge the support of MDW IV's Organizing Committee: Denice D. Denton, University of Washington; Philip E. Doepker, University of Dayton; Larry J. Leifer, Stanford University; John H. McMasters, The Boeing Company; Gregory B. Olson, Northwestern University; John W. Prados, University of Tennessee-Knoxville; Sheri D. Sheppard, Stanford University; and John W. Wesner, Carnegie Mellon University. Without them, there would be neither occasion nor need for the talk based on this paper, or, thusly, the paper itself.

Thanks to Joan Dym, John McMasters, John Prados and Sheri Sheppard for very useful comments on a previous draft of this paper, and to Eleanor Baum for providing data on Cooper Union's curriculum.

Finally, thanks as well to the many generous and continuing sponsors of this and prior Mudd Design Workshops: The Boeing Company, The GE Fund, Hughes Electronics, the National Science Foundation and Harvey Mudd College.

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## APPENDIX: THE HMC CURRICULUM

The Harvey Mudd College (HMC) undergraduate engineering curriculum has three 'stems' [39]: *engineering science*, with a focus on introductions to mechanics, thermodynamics, materials, and electrical and computer engineering; *systems engineering*, a set of three courses that focus on modeling and analyzing lumped-element models of physical systems; and *design*, including (1) a freshman design course [12, 30], (2) a sophomore course requiring students to design and make real tools, such as a hammer and a screwdriver, and to perform experiments to find detailed design parameters, and (3) Engineering Clinic projects in the junior and senior years [24-26]. HMC's engineering program is unified by the themes that *design* is the central activity of engineering [36]; that engineers typically design *systems*; and that such design requires good *models* of the physical systems [40].

Design, clearly an integral part of HMC's curriculum, 'peaks' in Clinic in the junior (3 cr.) and senior (6 cr.) years [24-26]. Since Clinic projects often require deep domain knowledge, it is reasonable to ask whether students can do in-depth design and development after a broad, general program? The answer is that students can and do, as evident in the willingness of companies to pay substantial fees for their HMC Clinic projects. In fact, students do first-rate design (and supporting analysis) because they know the fundamentals of the relevant discipline(s) and how to formulate and solve a technical problem. The Clinic project motivates them to acquire the needed domain depth. The Clinic setting focuses students' attention, and they work as they would in industry—on new and unfamiliar problems wherein they have to acquire and use new knowledge. They learn that design is not done *in vacuo*, but to meet a client's needs and to function within a specified system.

The HMC program couples a *broad* education in engineering fundamentals to a consistent exposure to design—from conceptual design and design methods in the first year through client-oriented, detail-design

experiences in the last two. Design is the integrator of our broad undergraduate program. (We have ample anecdotal and survey data from alumni that these experiences provide a framework for ‘lifelong learning’, and from companies that our graduates ‘hit the deck running’.

**Clive L. Dym** is the Fletcher Jones Professor of Engineering Design and Director of the Center for Design Education at Harvey Mudd College. His interests include design theory, knowledge-based (expert) systems for engineering design, and structural and applied mechanics. He has previously served at the University of Massachusetts at Amherst (1977–91), Bolt Beranek and Newman (1974–77), Carnegie Mellon University (1970–74), Institute for Defense Analyses (1969–70), and the State University of New York at Buffalo (1966–69). Dr. Dym completed the B.S.C.E. at Cooper Union (1964), an M.S. at Brooklyn Polytechnic Institute (1964), and the Ph.D. at Stanford University (1967). Dr. Dym has published more than 100 archival journal articles, proceedings papers and technical reports, has served on the editorial boards of several journals and has edited five volumes and written ten books, the latter including: *Engineering Design: A Synthesis of Views*, Cambridge University Press, 1994; and *Engineering Design: A Project-Based Introduction* (co-authored by P. Little), John Wiley & Sons, 1999 and 2003. He has been elected a Fellow of the Acoustical Society of America, the American Society of Mechanical Engineers, and the American Society of Civil Engineers, and is a member of the American Society of Engineering Education. Dr. Dym has won ASCE’s *Walter L. Huber Research Prize* (1980) ASEE’s *Western Electric Fund Award* (1983) and *Fred Merryfield Design Award* (2002), and was first runner-up for the *2001 Boeing Outstanding Engineering Educator Award*.