Session 1471

General Engineering at Harvey Mudd: 1957–2003

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Abstract
This paper describes the genesis and evolution of the philosophy of the Harvey Mudd College general engineering program. This program was established with a sound theoretical base strongly coupled to the realism of engineering practice. Thus, the paper also describes the development of the Harvey Mudd Clinic program — Harvey Mudd's three-semester *capstone* experience — to bring professional practice to on-campus students, as well as the first-year design course (E4) that exposes students to client-based design work as the *cornerstone* of its program. The emerging concept of engineering as the "liberal education of the 21st century" is also cited to emphasize the centrality of the engineering design paradigm — that is, design as the cornerstone or the *backbone* — in defining the discipline of Engineering. The implications of this analysis for undergraduate engineering education are discussed. The paper concludes with suggestions for realizing an undergraduate program in Engineering that is current, vital, distinctive and consistent with the idea of engineering being a single discipline.

Introduction
Engineering at Harvey Mudd College is a non-specialized multidisciplinary program, awarding an undesignated BS degree. The engineering major comprises one-third of the requirements for a student to graduate from the college, with another third in humanities and social science, and the remaining third in a mathematics and fundamental science common core. Engineering sciences and engineering systems courses complement the engineering design experience of the first-year projects course (E4) and the junior and senior year Engineering Clinic courses bringing professional practice to campus through industry-sponsored projects.

The program was recently classified [1] as a "philosophical Engineering program" based on certain defining characteristics, including a strong liberal education background and "the philosophy that such an education has intrinsic advantages over discipline-specific alternatives." This paper describes the genesis and evolution of the Harvey Mudd engineering philosophy growing out of a liberal arts environment and fashioning a new synthesis between a rigorous science base and professional engineering practice. This synthesis is made possible by the focus on engineering design as the cornerstone of the program. The centrality of the engineering design paradigm leads to a discussion of the application of this philosophy to a design-based approach to engineering education.

Context

The origin of the modern, *science-based engineering curriculum* is usually attributed to the Grinter report[2, 3]. That report reflected in part the thinking embodied in the famed Vannevar Bush Report[4]: greater public investment in science was warranted because of the impact of such "scientific" advances as radar and operations research during World War II. Further, as detailed by Seely[5], the Grinter report also reflected the culmination of the efforts of several engineering educators who had benefited from the European, more theoretical approach to engineering. (Seely[5] quotes Walker[6] 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.

The tenor of the times thus very much dictated an analytical, science-based approach to engineering education. By way of contrast, were one to start anew in the 21st century, the design of an engineering curriculum might be posed as a problem in engineering design. After all, to paraphrase a wonderful observation about *knowledge* offered by Stefik and Conway[7],

> *Engineering education is an artifact, worthy of design.*

This paraphrase is not meant to suggest that the engineering reform driven by the Grinter report was in any way random, thoughtless, or lacking in painstaking intellectual effort. Rather, it is meant to suggest another framework — the fundamental steps in the design of artifacts to keep in mind as the genesis and evolution of the Harvey Mudd model is detailed. Some of the basic steps in a structured, design-based approach would be[8]:

- 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?

The constituents, objectives, constraints, functions and metrics that underlie the design of the Harvey Mudd non-specialized program will emerge as the tale is told.

Genesis

In 1957, the first class of students began their studies at Harvey Mudd College. At the time it was the first college of engineering and science to be founded in this country for three decades. It saw itself as a new experiment in shaping the philosophy of engineering and science education in America. The purpose was expressed in the following lines from the College Catalog[9]:

> *"The College offers its students a general education in the humanities and social sciences and a specialized education in the physical sciences and engineering."*

The order of subject areas in the sentence is very telling. From the start, the central place of humanities and social sciences in the curriculum of the college was asserted. The paragraph continues:

> *"The College was founded in the belief that a special need exists for physical scientists and engineers with broad enough training in the social sciences and humanities to assume technical responsibility with an understanding of the relation of technology to the rest of society."*

This was the first published mission statement of the new college and it reflected the strong belief at the time that the humanities and social sciences had a new historical role to play in the education of engineers and scientists. It was recognized that the professional training of engineers and scientists would require utilitarian courses in report writing, communication, economics, psychology and management. Also courses in philosophy, literature and the arts would provide the necessary complement to the specialized vocational studies. However a new and significant goal was added to these requirements. The new role of the humanities and social sciences at the college was to train scientists and engineers to take on positions of general leadership in society. The first chair of the Department of Humanities and Social Sciences at Harvey Mudd captures the contemporary vision of the destiny of the next generation of engineers[10]:

> *"Tomorrow's engineer will have the fine attitude of the creative man … He will need more than knowledge of fundamentals; he must be flexible, fluent and original. …. The modern Renaissance finds him (**the engineer**) still the 'artist and empiric', but also the psychologist, the sociologist, the economist and in many respects the mover of worlds."*

This sense of the future power of engineers and scientists in society had a profound impact on the fashioning of the Harvey Mudd curriculum. The humanities and social sciences were to be the vehicle for creating the new "Renaissance" engineer/scientist.

There is more than a little kudos in these claims for the education of the future technical elite of our society.

The cachet of a "liberal education in science and engineering" was strengthened by the founding of the college as one of a group of affiliated undergraduate liberal arts colleges in Claremont which in 1957 included Pomona College, Claremont Men's College (later Claremont McKenna College) and Scripps College. Harvey Mudd College "drew strength from its membership" of the Associated Colleges of Claremont. It was natural for Harvey Mudd College to define and align itself with the liberal arts philosophy of its sister colleges.

The curricular impact of this emphasis on the humanities and social sciences was evident in the course offerings of the new college. From a total of 137 credit hours required for graduation, almost one third (42 credit hours) were required in the humanities and social sciences for all four majors (Chemistry, Engineering, Mathematics, Physics), the largest proportion of the curriculum for any engineering school in the country.

Thus, the philosophical basis for the genesis of the general engineering program at Harvey Mudd College can best be understood as a solution to a highly constrained design problem. Two primary constraints were in place before the first engineering faculty arrived on campus in 1959, over a year after the first students had started their studies. The first constraint was the large humanities and social science component of the curriculum outlined above. The second constraint can best be illustrated from the engineering program entry from the college catalog[9]:

> *"It is the purpose of the engineering curriculum to provide the student with a background which will permit him to make his choice of specialty, whether in industry or graduate school, after his undergraduate work is completed. This philosophy of engineering education is in close accord with recommendations of industrial leaders and professional engineering societies."*

There is a clear acknowledgement in this statement that the original conception of the engineering program was as a broad basic preparation in engineering science fundamentals with subsequent specialized engineering studies postponed until graduate school. This was very much in line with the expectation of the other majors at the college that the majority of students would go on to graduate study. In order to achieve this objective, all students, irrespective of major, were required to take a common core of science and mathematics courses in their first two years at the college. It was strongly felt that students were best served by enforcing adherence to the rule that the choice of major would be left until the completion of the students second year. The common core required another 51 credit hours of mathematics, chemistry and physics courses.

This left the engineering major with 44 credit hours (12 courses) in the junior and senior years, or about one third of the total credit hours required for graduation. It is not surprising, then, given the severe time constraints, that the initial course offerings of the engineering program were heavily oriented towards a general engineering science curriculum with five required courses in electrical, mechanical and materials engineering, an engineering lab course, two courses in engineering design and analysis and a choice of four technical electives in various engineering disciplines. So the original engineering curriculum at Harvey Mudd developed within constraints that allowed only a limited offering of engineering subject matter.

The prevailing philosophy then for the engineering program at the start of the college operations was that of producing an engineering graduate with an exceptionally broad liberal arts education, destined for graduate school and subsequent future leadership in society. Whether this was by conscious design or a *post-facto* rationalization can be debated. However, it is of interest to note that the "recommendations of industrial leaders and professional engineering societies" as stated above refers to a curriculum study at the college by representatives of industrial companies and engineering departments across the country. These recommendations actually called for a significantly larger proportion of engineering courses (55 credit hours) in the curriculum at the new college with a smaller humanities and social sciences component (32 credit hours)[12]. Clearly the recommendations were not adopted.

Evolution

It was not until the advent of the first engineering faculty to the new college that the seeds were planted from which the truly distinctive philosophy of the Harvey Mudd Engineering program would emerge. The first sign of a new path is the engineering program entry in the college catalog of 1962[11]:

> *"The engineering curriculum offers a fresh and exciting approach to engineering education. The course of study was planned in the belief that the primary function of engineering is design"*

Here is the unequivocal commitment of the new engineering faculty to design as the focus for the engineering curriculum. Here too is the start of the recognition that an undergraduate engineering program, even within a highly constrained environment, still has a mission to involve students in the practice of the profession they will be joining. This was not to be left until after graduation, in industry or graduate school. It was to be experienced directly by engineering students in the undergraduate engineering program. Thus began the quest for incorporating experiential learning of design and professional practice that was to culminate five years later in the full incorporation of Engineering Clinic in the program. The history of the Harvey Mudd Engineering Clinic program is documented elsewhere[13], but the 1967 course catalog describes its philosophy well[14]:

> *"The engineering curriculum is based on the premise that the primary function of engineering is design. The thorough background that the Harvey Mudd engineer acquires in mathematics, physics, chemistry and the fundamentals of engineering science provides him the resources necessary for undertaking challenging problems in engineering design. His design tasks may be drawn from the Engineering Clinic: an educational innovation developed at Harvey Mudd college to make it possible for teams of professors and students to work together as senior and junior colleagues. The questions they face are of the sort that professional engineers must face regularly; the solutions they devise must be satisfactory in practice as well as in theory. The College believes that this approach is most*

likely to produce engineers capable of adapting a changing technology to expanding human needs"

At the same time the engineering department broke through the confines of the college science/math core and introduced a new engineering design course (E4) for first year students. Warren Wilson, the first Chair of the Engineering Department presented the course objectives that were to become the goals of the engineering program for the next thirty years[15]:

1. Acquaint students with engineering practice;
2. Develop skills, by use, in computation;
3. Foster creative ability through projects;
4. Gain insight into management through group projects;
5. Develop appreciation for non-technical aspects of design; and
6. Foster willingness to responsibly attack open-ended problems.

The Clinic courses and the first-year design course expose students to client-based design problems. Each year about 25 new Clinic projects are initiated and taken to completion within the academic year. To date, over 700 projects have been carried out for some 250 different clients. If we needed any justification for a non-specialized general engineering program, then the very nature of Clinic projects provide that in ample measure. Clinic projects are inherently multidisciplinary, or more accurately non-disciplinary since there are no disciplines in the real world. Disciplines are an artifact of educational institutions and real world problems cannot be neatly packaged in individual discipline boxes. It made no sense to subdivide the curriculum into separate engineering fields, only to abandon these divisions when students face E4 or Clinic or, after they graduate, real world problems.

Clinic fundamentally changed the outlook of engineering education at Harvey Mudd. The engineering program aimed for a consistent exposure of engineering students to design. From conceptual design and design methods in the first year through client-oriented, detailed-design experiences in the last two years, design became the integrator of the general engineering program.

Another educational innovation was the concept of unifying the spectrum of engineering disciplines through the common methodology of systems engineering. A sequence of three required courses in lumped parameter linear systems was followed by the requirement that engineering majors also choose one of their technical electives in a subject area involving distributed parameter systems. Students could also elect advanced courses in nonlinear system simulation and system optimization. Again, it made no sense merely to stick a series of disparate engineering discipline courses outside the fabric of the design core. The systems courses are used as the vehicle for promoting the interdisciplinary insights necessary for creative design.

"Design is What It's All About"

As noted earlier, in the intervening years since the establishment of the Clinic program, the emphasis on design in the Harvey Mudd Engineering curriculum has deepened even further. Perhaps the most evident form has been the rededication of the first-year projects course, E4, into its current, more formal form, Engineering 4: Introduction to Engineering Design[16]. Designed as an introduction to conceptual design, and adopting a Clinic-style approach of student teams working for real, not-for-profit clients (e.g., schools, hospitals), the course has been successfully taught since 1992 as both a prerequisite for Clinic itself and a motivator that attracts students to the Engineering major. It has also served as a pedagogical laboratory, out of which has evolved a studio style of teaching the course, very much in the traditions of our colleagues in art and architecture[17]. And while the idea of teaching design to first-year students was controversial in the early 1990s — after all, "Engineering students don't know enough to do design so early in their studies" — the course has been widely emulated[18] and spawned a textbook that has been adopted at some 60 schools and is already in its second edition[8].

The emphasis on design in the Harvey Mudd Engineering program also led to the establishment of the Center for Design Education (CDE). The CDE's main activity thus far has been to bring together design educators, design researchers and design practitioners to talk about issues of design education in a biennial series of Mudd Design Workshops[19–22]. The workshops have been held on a variety of topics (e.g., computing futures in design, designing design education, social dimensions of design, and designing engineering design education). They have served to bring together disparate communities of design-oriented professionals in a setting that has enabled and fostered much-needed communication and interaction.

Clearly, the notion of a broad, unspecialized curriculum and the emphasis on design as engineering's distinguishing activity[23] are synergetic strengths. They clearly and emphatically answer the most pressing questions that underly the engineering education enterprise: Why are we doing this?, and Why are we doing it just this way?

Further, the broad, design-based approach blends well with an interesting definition of engineering (and, in parallel, science) put forward by Wulf: In the same way that *science* is both a *body of knowledge* and a *process*, so too does *engineering refer to the* ***processes*** by which the body of knowledge and artifacts of *technology* are created[24]. Among other things, this separation or decomposition of the artifacts created from the processes that create them suggests that a curriculum that stresses specific, disciplinary bodies of knowledge may be hiding or obscuring a more appropriate emphasis on process, and especially on process as it is actually applied in the real, multidisciplinary world. It also suggests that, in the terminology of the design process, one new curricular objective and one revised constraint should be considered for engineering programs[25]:

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 ($\text{i.e., an engineering program} = \sum \text{skills} + \text{experiences}$), 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.

It is also interesting to observe that a broad, design-based program can meet and address a broader, unified vision of engineering as a single "discipline of design." As a result, many of the broader attributes and expectations that one would like to identify with engineering fall easily and naturally under general engineering's umbrella, including:

- engineering itself emerging as a new, unified field as traditional (engineering) disciplinary boundaries increasingly blur;
- the perceptions of engineers shift from their being "problem solvers" to being "problem identifiers" or "problem configurators";
- engineering emerging as a path to other, broader careers such as business, law, and politics; and
- engineering emerging as *the* "liberal education of the 21st century."

Finally, it is Harvey Mudd's experience that a broad, design-based program successfully, and even splendidly, addresses many of the commonly-heard concerns about engineering education, including:

- the content and presentation of the curriculum;
- the effectiveness of learning by students;
- the retention of those students in the classroom; and
- the graduation of appropriately-educated engineering professionals to maintain and enhance America's technologically-rich, service-oriented economy and lifestyle.

In this connection, and as providing but one (relatively minor) assessment measure, note that Harvey Mudd's Engineering program is well known and invariably ranks at or near the top of lists of "best" programs (e.g., ranked second in the 2003 *U. S. News* ranking[26] of "Best Undergraduate Engineering Programs"). We also 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."

Conclusions

The "philosophy" of general engineering at Harvey Mudd developed as a response to a constrained college curriculum emphasizing the liberal arts. Breaking the mold of an "engineering science" niche, the engineering program stamped a new philosophy of design through professional practice. The general engineering program at Harvey Mudd transcends the arguments that cite the advantages or disadvantages of broad-based versus specialized curricula. The philosophy can be summarized as follows:

There is a single unified discipline of engineering. It is rooted in design and it can be taught as a design-based process. Education in this discipline calls for active engagement in experiential learning of the engineering profession by direct encounter with authentic client-based design problems. Design skills and methodology are learnt from the outset of the program to provide the context for all subsequent studies in the program. Creative design needs the interdisciplinary outlook provided by systems thinking. Domain depth is motivated and acquired by the exigencies of solving real world problems.

The engineering program encompasses a rigorous theoretical grounding in fundamental engineering science and mathematics, a unified treatment of engineering systems, the art and practice of engineering experimentation, the learning of professional project management, communication and teamwork skills to meet a clients needs and the provision of new and unfamiliar design problems each year through the Engineering Clinic.

Acknowledgments
The Harvey Mudd Engineering program is both sufficiently young and fortunate that we are able to acknowledge the inspiration and examples of our Founding Fathers and their immediate successors, all of whom are still among us, including Jack Alford, Mack Gilkeson, Jim Monson, Rich Phillips, Sedat Serdengeti, Harry Williams, and Tom Woodson. We are also indebted to our current colleagues who daily inspire us afresh with their continuing commitment to our shared vision.

Appendix: Harvey Mudd's General Engineering Program
The Harvey Mudd College Engineering curriculum has three "stems" [2003 catalogue]: *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[16, 8], (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[13]. HMC's engineering program is unified by the themes that *design* is the central activity of engineering[23]; that engineers typically design *systems*; and that such design requires good *models* of the physical systems[27].

Design, clearly an integral part of HMC's curriculum, "peaks" in Clinic in the junior (3 cr.) and senior (6 cr.) years[13]. 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.

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