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An Optimal Engineering Education: The BSE at a Liberal Arts College

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1 Abstract

How best do we educate an engineer whose career could last over 40 years? This paper examines the structure of the BSE program at Calvin College, a comprehensive liberal arts college in the Midwest. This engineering program emphasizes breadth, contextualization, and normative design.

For several decades, most engineering schools followed a trend of ever increasing focus on the details of one particular sub-discipline of engineering. Our program emphasizes breadth not only across engineering disciplines, but also uses a solid foundation in the liberal arts that provides the broad worldview on which effective leadership arises. Our outcome-based assessment of recent years appears to reflect an industry need for more breadth and thus less depth. While depth provides good preparation for entry level positions and the first five years or so of a career, contextualization better supports the full career span, which requires continual self-learning and often has leadership opportunities in technical and non-technical areas.

While engineering analytical skills are important, good design requires good communication, critical evaluation, creativity, and integrative multidisciplinary problem-solving approaches – skills that a liberal arts foundation provides. Integrative design implies normative design, *i.e.,* design with ethical and social considerations intrinsic to the entire process.

The emphasis on broad fundamentals and normative design is not without challenges. This approach tends to generate programs that require more courses, are less flexible, and are less recognized than more specialized programs. We conclude by addressing the challenges and opportunities faced by our program and similar programs.

2 What is the Goal?

What is the goal of an engineering education? If graduates are our product, what is the specification of this product? Perhaps we should focus on the initial delivery, which for most graduates is to an entry-level engineering position and for a smaller number, it is to graduate

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school. Indeed, the requirements of employers and graduates schools should significantly influence our curriculum and pedagogy. However, our product must last much longer! An undergraduate engineering education must prepare the student for her entire career, which may last over 40 years. It must provide a foundation for life-long learning and career development.

3 What do Key Customers Require?

Like practicing engineers, engineering educators also produce a product. From a design point of view, it is necessary to clearly define our criteria in order to best achieve the optimal outcome. There is a need for some breadth of education, both technically and in the liberal arts. There is also a need for some depth in one or more specific technical areas. The catch, of course, is that students must be prepared for such a wide array of possible positions following graduation.

The vast majority of engineering graduates enter the workforce directly, so programs should logically be tailored to best meet this need. But even that does not narrow things enough. The span of industries where a student might take the first job is vast, each requiring different specialized knowledge. Furthermore, anticipating some career changes, it becomes impossible to predict the specialized technical knowledge any one student will require, let alone an entire class of students.

But should this be the goal of an engineering degree, especially while it remains a predominantly four year professional degree? Engineering education needs to focus on teaching students how to learn; indeed to be life-long learners (as ABET 2000 has identified). This is the only practical solution.

On the other hand, students must enter the first job with an adequate base of knowledge, and employers are not generally finding this to be the case with current educational methods. In fact, a survey of engineering managers found that managers identify written and oral communication and teamworking skills as generally inadequate in engineers within five years of graduation. The same survey noted that graduating students recognize their need for skills in these areas, but despite recent education reforms to add these skills, the students felt inadequately prepared by schooling[1].

Certainly, some technical depth is needed, too. Depth should not be so specialized that it comes at the expense of breadth (either technical *or* liberal arts). An experience of learning something in depth can set the pattern for lifelong learners to follow, *provided* they have sufficient breadth to be aware of the things they may need to learn in depth in the future. It is this breadth that is not so easily picked up on the job, where the work may in fact be quite narrow for a time. It should be the role of the entire undergraduate education to open a student's mind, as National Academy of Engineers' president Bill Wulf puts it, "to appreciate the human dimensions of technology, understand global issues, be sensitive to cultural diversity, and know how to communicate effectively."[2] Once a sense of wonder and respect for these issues is well planted through a variety of undergraduate courses, then a lifetime of experiences can truly lead to a lifetime of growth.

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Students do *not* necessarily recognize their need for a broader perspective on their own. A survey by Benefield, *et al*, found that "diverse types of knowledge are viewed as more important by alumni and industry than they are by faculty and students. Experience with diverse types of people and with problem-solving groups of various compositions is viewed as more important by alumni and industry than it is by faculty and students….Communication skills are considered very important by alumni, faculty and industry. However, students seem to place a low value on these skills."[3]

Perhaps an overhaul of education is needed, as Clive Dym from Harvey Mudd has called for: "We should recognize that breadth is likely a far greater strength than the narrowness of depth at this level of education".[4] There is evidence of a disconnect between what faculty see as important, based on their own experiences, and what employers, the ultimate end-users of the faculty's product, are asking for. A survey found that faculty groups "rated math and science skills second and … rated depth and breadth of technical skills to be third. But both the industry group and the alumni rated communication skills, professionalism and ethics, and a responsible and open mind, above both depth and breadth of technical skills and math and science skill. This is indicative of the mounting evidence that employers, especially those that are joining or that have joined the quality revolution, are desperate for people who do not have to learn on the job how to fit into a team-centered culture where communication, interpersonal skills, and professionalism, are as important as technical skills." [5]

4 Is the Engineer Primarily a Designer?

"Don't let it turn into a science project." This may seem a strange turn of phrase to an academician, but it is well understood in engineering industry. Engineering managers do not want engineers to spend inordinate amounts of time doing research that does not directly aid in finishing a product design in a timely manner. A "science project" may not only produce some interesting information but may also result in general principles describing a technology. Nevertheless, such pursuits are discouraged in industry because they are not obviously "value added activities." Perplexingly, much of the engineering education curriculum is geared precisely towards producing researchers who are quite good at pursuing "science projects," rather than designers who can quickly develop a good product. "Engineering graduates, though well versed in technical theory, are oftentimes deficient in their ability to transfer theoretical knowledge to industrial applications."[6]

Most engineers are designers, not researchers. Engineering design is the development of a product or process to solve a specified problem using mathematical and scientific knowledge. A design must effectively solve a problem or, in some cases, provide some valuable new benefit. Design work proceeds from a problem statement (which is sometimes ambiguous) to a specific solution – a product of technology that solves the problem. Most designs are developed under cost and schedule constraints. Reuse and imitation of existing designs are often valuable approaches to produce a design quickly. Copying is not only allowed but encouraged in this environment, as long as patent or copyright infringement is avoided. Using all or part of an existing design not only reduces design time, but also reduces risk, since the strengths and weaknesses of the existing design are better understood from experience. Where a design

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includes an innovative, novel feature, it is often considered proprietary. The details are kept secret if possible, or else patent protection is sought. The engineer is rewarded for speed in development because this reduces time to market as well as design costs.

Most engineering educators are researchers, not designers. Research is the systematic investigation of an area of knowledge in order to identify new, general principles. Research often starts from specific data or cases and works towards broad, general knowledge that characterizes the overall principles involved. The quality of research is typically measured by the number of scholarly papers published. Publishable research must be innovative – something new. It may even include negative results (something that did not work) if this is new knowledge. Imitation of others is discouraged. Engineering educators are part of the higher education enterprise where research is rewarded. "Our curricula are institutionalized within an engineering science model of engineering and delivered within academic cultures that conform to a scientific research enterprise."[7]

Thus, what engineering educators should teach (design) is not what they themselves must do to succeed (research). The closest much research gets to design is perhaps the design of experimental equipment. But, this is not the design of a product or a manufacturing process that most of the students of engineering educators need to understand. Engineering science and analysis is the strength of many engineering educators. Certainly these elements play into good design, but by themselves do not constitute design.

Fortunately, many of the skills needed for design are also requisite for research. Design requires creativity, engineering analytical skills, critical evaluation skills, communication skills, and multi-disciplinary problem solving skills.

Good designers must be creative and able to think in divergent paths. Most problems are underspecified, leading to many possible solutions. Identifying the most viable solutions that best serve a variety of often conflicting design criteria requires originality and imagination. Proposed solutions may include completely novel approaches, but may also find ways to use existing technology in new ways.

Good designers must have strong engineering analytical skills. Once a set of proposed solutions is generated, they must be evaluated for their suitability to solve the specified problem and for how well they stack up against the design criteria. Analysis uses mathematical and scientific principles to predict the performance of each proposed solution on each of the criteria of interest. Optimized designs require systematic investigation of the solution space – perhaps exhaustively, perhaps not, depending on the schedule constraints. For example, an analog circuit *design* problem might ask "What circuit will produce the desired amplification at low cost and high fidelity?" The *analysis* of each proposed solution will simply ask "What amplification, at what fidelity, does this particular circuit produce?"

Good designers must have excellent critical evaluation skills. By this we mean something different than analysis skills, which are more technical in nature. Critical evaluation is the ability to carefully reason about a particular proposed solution, seeing its flaws and its strengths. Such thinking is required to tease out additional design criteria that are significant but were missed the

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first time through. Such thinking is required to identify broader issues, such as those related to safety or legality. Critical thinking ensures that the right analysis questions are asked.

Good designers must be proficient communicators. A complex design must be understood by engineering team members during a peer review, by managers overseeing the project, by marketers attempting to sell the product, by customers considering purchasing the product, by regulators, and more. Communicating the essence of the design to each of these audiences requires skills in graphical, oral, and written communication. The designer must be adept with a variety of communication media, from email, to written reports, to visual presentations. She must be able to work with words, charts, figures, statistics, drawings, orthographic projections, mathematical equations, computational algorithms, and more.

Finally, good designers must be multi-disciplinary problem solvers. While the engineering education curriculum is cleanly split amongst various sub-disciplines, the real engineering products are never so easily broken down into constituent parts. The designer must be at least cognizant of many different disciplines that come together in any specific technological product, and must often have significant expertise in a few of them.

5 How Has Calvin College Addressed These Challenges?

5.1 Introduction

The engineering program at Calvin College is characterized by an emphasis on breadth, contextualization, and normative design. We believe our students are well-served by the placement of their professional education within the context of a comprehensive liberal arts college. Since a four year program cannot do everything, we have given up some upper- level electives and in-depth course sequences in sub-disciplines – even though these are common in most engineering programs. While the value of such courses is clear, we believe an engineering graduate with the appropriate fundamentals can acquire this knowledge either in graduate school or through self-study when job requirements dictate.

Our approach is best communicated by our program objectives:

> Those graduating with a BSE degree from Calvin College will be:
>
> 1. <u>individuals</u> who are firmly grounded in the basic principles and skills in engineering, mathematics, science, and the humanities, for correct, perceptive, and sensitive problem assessment at a level appropriate for both entry level work in industry and in graduate school;
>
> 2. <u>designers</u> who are able to creatively bring a project from problem statement to final design while realizing the interdisciplinary and interdependent character of the engineering profession;
>
> 3. <u>servants</u> whose Christian faith leads them to an engineering career of action and involvement, to personal piety, integrity, and social responsibility.

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5.2 Strong Liberal Arts

Calvin College has extensive general education requirements, taken by all students. It includes at least 23 courses with 68 credits over a broad range of human knowledge. It is not possible for those students in the professional programs to take the standard general education and still graduate in four years. Thus, they are granted a requirement reduction. Still, engineering students take 70% of this large requirement. Courses are included in the following areas:

- Written Rhetoric
- Oral Rhetoric
- Developing a Christian Mind
- History of the West and the World
- Philosophical Foundations
- Societal Structures in North America
- Religion
- Literature
- The Arts
- Cross-Cultural Engagement
- Integrative Studies
- Health and Fitness

In addition there are two free electives where additional liberal arts courses can be taken. Thus, the Calvin engineering student is exposed to a broad foundation of human knowledge with a global perspective. These courses are taken with the general student body; thus, the perspectives of students with philosophy, English, history, *etc*. majors are experienced, rather than only that of other engineering students.

5.3 Solid Foundations in the Sciences

The engineering curriculum at Calvin College is designed to provide a solid foundation in the sciences and mathematics upon which understanding of the physical world is based.

An engineering education cannot cut corners on the foundational sciences. Therefore our program includes:

- Two and a half years of Math
- A year of Physics
- A year of Chemistry
- A science elective

One advantage of a small liberal arts college setting is that the engineering department closely interacts with the supporting science departments. We have the opportunity for extensive cooperation between the engineering department and faculty in the sciences who teach our service courses. One example of the fruits of this collaboration is a new first year course which combines topics in materials science with chemistry. The course is team-taught by chemistry and engineering faculty.

5.4 Interdisciplinary Engineering

An engineer's career is generally much broader than the scope of any one sub-discipline. Therefore all students take courses in each of the four major areas of engineering (Chemical, Civil, Electrical/Computer, and Mechanical.) These are:

- Fundamentals of Design

- Graphical Communications
- Statics and Dynamics
- Materials Science with Lab
- Electrical Circuits and Electronics with Lab
- Conservation Laws and Thermodynamics

At Calvin College, our commitment to a general engineering degree stems from our belief that most engineering problems are interdisciplinary in nature. While engineering analysis is often focused within specific sub-disciplines, design/manufacturing/construction usually requires an interdisciplinary background. Thus, students are best served by a broad engineering foundation which gives them the language, methods, and applications related to a broad spectrum of engineering disciplines. For the first two years of the program, all engineering students take a set of common courses introducing them to a variety of engineering topics. In addition to broadening the student's education, these courses result in a more informed decision of which of the four concentrations they will pursue in the junior and senior years. This decision is not made until the end of the sophomore year when students apply to enter a concentration. They also have the opportunity to interact with students who will pursue a different concentration. Cohorts of students in a specific concentration are not established until the junior year.

Our capstone course sequence, the Senior Design Project, is in many ways typical of most engineering programs' capstone courses. However, all engineering students take the same two courses. These courses are team taught by engineering professors, one from each of the four concentrations. Thus, the student is provided with exposure to senior level work across the broad spectrum of engineering. In addition, interdisciplinary project teams are commonly formed.

5.5 Fundamentals of an Engineering Sub-Discipline

Obviously, someone hired as an entry level engineer needs to have adequate knowledge to solve appropriate problems. Employers expect that the graduates that they hire will be prepared in an engineering sub-discipline. Our curriculum allows students to focus on a particular type of engineering in the second two years of the program. Each of the engineering sub-disciplines (Chemical Engineering, Civil Engineering, Electrical/Computer Engineering, and Mechanical Engineering) involves two sequences of courses working from fundamentals to analysis to design. The emphasis is on the common foundations to each of the sub-disciplines. These courses adequately prepare the student for entry level positions in industry and government or for graduate school.

5.6 Design Emphasis

Calvin's engineering program has always had a design emphasis, first in our pre-engineering program and since 1985 in our BSE program. When engineering education moved aggressively toward engineering science in the 1960's and 1970's, we kept our focus on design. We believe we have been a leader in having a design emphasis in engineering education. Currently, the design focus starts with the first course in engineering, in which students are required to do a service learning project. The students work with real customers and produce and deliver actual

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devices. Teams design and build a device or system to help people with various disabilities to perform a job more efficiently.

When the profession, led by ABET with significant input from industry, began to return to more significant design emphasis in the last decade, Calvin seemed to lose our leadership position. We have not lost that emphasis, but others have surpassed us.

To regain our leadership position, we recently developed the following goals for design throughout the curriculum. We will have 1) a team-based design project in each of the five engineering courses in the first two years, 2) at least one design project during the upper level courses in each concentration, 3) continued strong senior design project courses. We have met goals two and three as of this school year. Three of five lower level courses now have a design project with plans to have a design project in the other two courses within two years.

Ethics and integrity of design are critical elements for the education of the engineering professional. We address these areas through seven design norms. Presented starting in the first year, they culminate as a key component of the senior design project. Design norms are general principles that relate how design "ought" to be done, or moral guidelines. Normative design attempts to balance design trade-offs not only among technical/economic constraints but also among ethical and social constricts. Such norms force the engineer to consider the broad impact of the design on society. These design norms are:

- Cultural Appropriateness
- Transparency
- Stewardship
- Integrity
- Justice
- Caring
- Trust

See Ermer and VanderLeest[8] for a detailed presentation of these design norms.

5.7 Emphasis on Industrial Experiences

The overwhelming majority of engineering graduates will have a career in industry. Therefore, we believe the student engineer must have significant exposure to industry during their education. We address this need in three ways.

First, faculty professional development expectations emphasize consulting and industrial experience. A relatively recent development has been for faculty to include industry experiences as part or all of their sabbatical leaves. We value industry experience highly in recruiting new faculty as well.

Second, our faculty has significant industrial experience. Six of the fourteen faculty members have between 12 and 30 years in industry. The average is 22 years with at least one faculty member in each concentration having this significant experience. This experience provides a

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different and, we believe, better context to teach engineering. This context is particularly valuable in mentoring design teams during the many courses with design projects.

Third, a mentoring experience with an engineer in industry is required of all first-year engineering students. Also, we have a very active summer internship program. Over 90% of our juniors have an internship experience, some internationally. In addition, many of our sophomores and some first-year students have internships. Release time has been provided to professors to set up and evaluate these internships to ensure high quality.

6 The Challenge Now and Ahead

The approach Calvin has taken to structuring its program has many benefits but is not without its challenges. This section of the paper will highlight some of the issues that have arisen in the past and will need to be addressed going into the future.

6.1 A Very Full Program

Typical bachelor of science students at Calvin need 124 semester hours to graduate. The engineering student needs a minimum of 138. Although it is typical for our students to graduate in 4 years (80% have done so over the past 4 years), graduating in 4 years requires carrying loads of 16 or 17 semester hours on average. Thus, we have no room to respond to new areas while maintaining our educational philosophy. For example, biology has become an important part of a Chemical Engineering education. Most programs are requiring one or two biology courses. Yet, we have no room within our chemical concentration program to add even one biology course. We foresee a similar problem arising with nanotechnology and our mechanical concentration.

6.2 Students Do Not Value the Liberal Arts

An ongoing challenge is getting engineering students, who come into college with a primary interest and strength in the scientific/technical material, to appreciate the contributions of the courses outside their major, especially those that fall under the college general education requirements (known as the "core curriculum"). Many students exhibit a "check the box" mentality toward their core courses, assuming that what is taught in these courses is not interesting, not relevant, too simple, or too difficult. It is challenging to convince a young person, with very little experience of the kinds of skills and attitudes that will be valuable to his life's work, to appreciate how much they might need to grow in these areas.

There are several ways to address this. One is to encourage engineering faculty to emphasize the usefulness of cultural context as part of the technical content of their courses. The engineering faculty should frequently tie together the societal impact and sense of personal responsibility with engineering, since the faculty outside the engineering department teaching the liberal arts courses will not have the experience necessary to make these connections.

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Another helpful influence is for students to be exposed as much as possible to engineering practitioners. These engineers almost unanimously emphasize the importance of "soft skills" and a broad context for success. This means encouraging faculty to maintain ties with industry, bringing in engineers from industry for seminars and guest lectures, and providing mentoring opportunities for our students in local businesses. A particularly effective experience this year was a panel of members from our industrial advisory council talking about what it takes to be a successful engineer in a number of different settings.

6.3 The Knowledge Explosion (Specialization vs. Generalization)

Calvin continues to struggle with the challenge of providing a broad education while the number of sub-disciplines and the amount and complexity of their subject matter continues to grow. Our program can be characterized as a generalized one. However, with the knowledge explosion, engineering education is becoming more and more specialized. A key challenge for the future is whether we can maintain our broad, generalized program with its many strengths yet still provide the appropriate depth of technical education to prepare our students for entry level positions in industry or graduate schools. Much depends on how other engineering programs respond to the needs of industry in providing a broader, more liberally educated engineer. If these program so respond, they must limit the depth of specialization and then we will be able to continue with our current philosophy. If not, the challenge remains.

7 Conclusions

Does this approach work? The following quotes from graduates of the class of 1993, taken from the 2003 assessment, are representative of alumni feedback from various assessments:

> "I enjoyed several influences at Calvin that were not commonly experienced by my professional peers:
>
> - Sharing my college years with many non-technical peers, with their distinctive world views.
> - Minoring in Philosophy with its distinctive disciplines.
> - Studying a liberal arts curriculum, with its broad range of perspectives on problem solving.
>
> These influences have contributed to unusual interpersonal & problem-solving skills that have served me very well in many areas of my life."

> "Calvin College taught me how to learn. Once you know that, you can teach yourself new skills as the industry changes, keeping yourself relevant in your field. As a Calvin College graduate I was better prepared than many graduates from large prestigious universities that teach cookbook engineering. Calvin Engineering grads have been equipped as well as grads from MIT, Stanford & Carnegie Mellon. Also having the Christian perspective is very good."

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"Calvin not only provided a proper engineering education it helped instill a personal character which has transferred to my professional life as well. Honesty, trustworthiness, competency is part of both my personal and professional life."

"The engineering program at Calvin taught me to be a professional, which is something it appears that most other engineering programs do not teach. Also the emphasis placed on social responsibility or social impact of design sets me apart from my peers in some cases. The emphasis on oral and written communication skills has also proven to be a vital asset."

In conclusion, we believe that we have the right approach. As in any engineering design, designing an optimal curriculum requires trade-offs between many valuable components. We still continue to improve, but believe our emphasis on breadth, liberal arts, and design serves our students well over the course of their entire careers.

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