Evidence for Design of Mechanical Engineering Curriculum

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Evidence for design of mechanical engineering curriculum

Abstract
Numerous sources of evidence can be used in design of mechanical engineering curriculum, from reports from large organizations, such as ASME’s Vision 2030, NAE’s Engineer of 2020, ABET Criteria, and NCEES’s exam specifications, to peer-reviewed journal articles, textbooks, handbooks, job advertisements, and contact with working engineers. Each source has different benefits and limitations. For example, reports from organizations are too broad to specify which textbook sections can be skipped without consequences. Therefore, a synthesis of numerous sources is necessary for design of an engineering curriculum. There is broad consensus that early-career mechanical engineers need more practical experience and better integration of technical and professional skills. There is less clarity on the value of any given technical topic. Even so, handbooks, working engineers, and job advertisements can support development of useful technical curriculum content.

Introduction
Engineering curriculum evolves gradually over time in response to technological developments, institutional pressures, new pedagogical methods, and shifts in industry demand. Engineering curriculum is rarely designed—that is, developed to meet a need by iteratively inventing options and selecting the best ones based on evidence.

Engineering curriculum has evolved in ways that are inconsistently tied to evidence. One illustrative example of evolution of engineering curriculum is the ASEE-commissioned “Report of the Committee on Evaluation of Engineering Education”, the so-called Grinter report from 1955 [1]. The first draft of the Grinter report called for two models of engineering education, with most engineering students being prepared for industry and the remainder given a more advanced scientific preparation [2]. However, most engineering schools, wanting access to government research funding, protested, leading to the final report calling for a single model with an increased focus on science.

The Grinter report recommended that all engineers should gain a background in the six engineering sciences of solid mechanics, fluid mechanics, thermodynamics, heat and mass transfer, electricity, and materials. The report noted that, at the time, few curricula required students to have exposure to all six of these areas. This enumeration of the six engineering sciences is, itself, unscientific, being made without evidence of what engineers do and what educators can do to prepare engineers for professional practice. Even so, these six engineering
sciences have come to constitute much of the structure of undergraduate mechanical engineering curriculum.

The Committee collected evidence from industry on what education they expect of graduates. Industry “indicated no criticism of the technical competence of engineers but raised questions concerning (1) the adequacy of their background in basic science, engineering science, and humanistic fields and (2) concerning their capacity for effective communication. This reaction with regard to the inadequacy of basic science and cultural background was essentially unanimous.”

The reforms called for by the Grinter report were not consistently implemented: although the Grinter report led to an increased emphasis and standardization on basic and engineering sciences, cultural background and professional skills such as communication still do not have much emphasis in most engineering curricula. Furthermore, although the report called for all engineers to have a background in all six engineering sciences, this requirement is clearly not held in many disciplines; solid mechanics and electricity are not required in many chemical engineering programs, civil engineering students rarely take courses in electricity or thermodynamics, and electrical engineers focus on electricity to the exclusion of almost all other engineering sciences. Mechanical engineering is the main discipline in which a background in all of these sciences is expected. Is there a reason—apart from appeal to tradition—to continue to emphasize these six engineering sciences in mechanical engineering? Furthermore, what elements of ME professional practice are not given their due in ME education?

To truly design a mechanical engineering curriculum requires consideration of evidence of what mechanical engineers do and how to prepare people to do those things. This paper presents several complementary sources of evidence for what early-career engineers need to be capable of. Organizations have produced studies of the future of the field that give large-scale perspective. Peer-reviewed journal articles report survey data on what specific skills engineers use. Members of industrial advisory boards can share their personal perspectives on curriculum. Textbooks are not evidence of what is important for working engineers but they are worth considering when determining how to organize a curriculum. Markets convey information on what engineers do; for example, handbooks show what information is relevant to engineers and job advertisements indicate what skills are in demand and what aspects of those skills are most meaningful. This paper focuses on design of ABET-accredited bachelor’s degree programs in mechanical engineering but is relevant to mechanical engineering concentrations within general engineering programs; furthermore, many of the sources are relevant to all engineering disciplines.

To summarize these sources, studies by large organizations and small teams of academics consistently show that engineering curriculum lacks rigor, not with respect to coverage of technical facts, but in integrating technical and professional skills through practical experiences. This lack of rigor is so substantial that it is hard to find evidence that mechanical engineering students need more particular technical content to be prepared for professional practice; that is, the problem with mechanical engineering education is not mechanical. Although engineers are distinguished from graduates in other fields by their technical expertise, paradoxically, there is minimal evidence that every mechanical engineer needs to learn any given piece of technical information; these findings hold not just for mechanical engineering but for most engineering disciplines.
This problem with rigor is so significant that studies based on surveys of alumni and industry do not reveal a standard for ME technical curriculum content. Fortunately, handbooks, job advertisements, and working mechanical engineers can authentically guide an engineering program to being distinctly mechanical. This paper concludes with a summary of some perspectives, based on this evidence, for implementing an ME curriculum that is based on evidence of what MEs do.

**Documents from organizations**

*Mechanical Engineering*

The most canonical document for design of specifically *mechanical* engineering curriculum is the Vision 2030 Report from the American Society of Mechanical Engineers [3]. The Vision 2030 committee was convened to determine how ME degree programs should change in response to the rapid changes in ME practice. One influence on the project is the NSF 5XME workshops which were held in response to the challenge of educating mechanical engineers who can be five times as valuable as their global competition (who can do similar technical work at one-fifth of the wages). The report is also based on previous reports from other organizations and people, as well as on survey results.

Among other things, the survey results showed that industry is satisfied with BSME hires’ technical fundamentals but sees the greatest weakness of BSME hires as being “Practical experience—how devices are made and work” and communication skills. Broadly, Vision 2030 established the following goals for ME degree programs:

1. Greater innovation and creativity
2. More flexible curricula
3. Richer practice-based experience for students
4. Stronger professional skills for students
5. Technical depth specialization
6. Greater diversity among students and faculty
7. New balance of faculty skills
8. Enhance mechanical engineering technology

Note that most of the goals regarding curriculum are broad and that specific technical content is not a concern.

ASME is responsible for specifying the ABET criteria that are specific to ME curriculum; these program criteria are the most forceful statement of what is essential to ME education. The only required courses for ME curriculum are multivariable calculus and differential equations; the only additional requirement on technical content is that students should be able “to work professionally in either thermal or mechanical systems while requiring topics in each area”—previously, programs had to prepare students to work professionally in both thermal and mechanical systems but that requirement was loosened to its present form in response to the
second goal from Vision 2030, curricular flexibility. Finally, ME curricula must enable students “to model, analyze, design, and realize physical systems, components or processes”; this is certainly a goal for many engineering disciplines.

Preceding the Vision 2030 effort was the ASME Body of Knowledge task force, which led to “A Vision of The Future of Mechanical Engineering Education” (2004). A body of knowledge is a description of the knowledge needed in a given profession. There are several body of knowledge documents, such as for civil engineering and project management. Note that the ASME Body of Knowledge task force did not produce an actual body of knowledge. Furthermore, the National Society of Professional Engineers (NSPE) later developed a body of knowledge and sought comment from several engineering societies; IEEE-USA, AIChE, ASCE, and ASABE provided comments but ASME and three other societies did not.

In summary, over the past 15 years, ASME has given broad, high-level guidance for ME curricular reform while consistently giving limited specific recommendations regarding technical content. Why might this be? Will this stance correspond to a decrease in rigor and thus a diminution of the value of a degree in ME? No.

Rigor, or thoroughness, in ME education is being reconceptualized from thoroughness of technical preparation alone to thoroughly relating technical fundamentals with practice: practical knowledge and professional skills. This shift is called for by industry; meanwhile educators generally do not recognize the need for this shift [3].

**Broader Engineering**

Vision 2030 is based, in part, on previous documents from other organizations [3]. Here, some of these documents and their relevance to Vision 2030 and ME education are summarized. The NAE reports *The Engineer of 2020* [4] and *Educating the Engineer of 2020* [5] point to the increasing rate of technological change and the rising significance of global and environmental issues; in response, the committee calls for undergraduate engineering education to be more flexible, preparing students to be interdisciplinary thinkers and lifelong learners. The ASME 2028 Vision for Mechanical Engineering [6] recognizes the challenges of sustainable development as billions of people join the global middle class and acknowledges the increasing interconnectedness of humanity; these factors require engineers to be increasingly skilled at adaptation, analyzing complex systems, collaboration, and management. Duderstadt’s “Engineering for a Changing World” argues that American engineers need to be able to add more value than their international competition who earn lower wages; to remain competitive, American engineers should be more broadly-educated, innovative, entrepreneurial, and prepared for global challenges [7]. Recognizing the difficulties in attracting young people—especially women and members of underrepresented minority groups—the NAE Committee on Public Understanding of Engineering Messages developed a positioning statement for the profession focusing on creativity and helping people; naturally, ME curriculum will need to change to reflect those aspirations [8]. A Carnegie Foundation for the Advancement of Teaching (CFAT) book, *Educating Engineers*, reporting on observations of particular ME and EE programs, argues for a transition from a linear components model of education focused on engineering science to a networked model in which professional skills, design, and engineering science are integrated across the curriculum [9]. Taken together,
the consensus across organizations such as ASME, NAE, and CFAT, is that engineering education should be more open-ended, design-focused, authentic, integrative of technical and professional skills, and relevant to global issues.

More recently, the National Academy of Engineering recently released a report, *Understanding the Educational and Career Pathways of Engineers* [10], with findings on careers for people with BS degrees in engineering disciplines; many of these findings are based on the NSF Scientists and Engineers Statistical Data System (SESTAT). Less than half (46.1%) of BS engineering graduates have jobs that are classified by NSF as engineering. Only 31.2% of BS engineering graduates have jobs where the primary activities are “engineering”, i.e., research, development, design, and quality management. With that said, most BS engineering graduates have careers in which they use their degrees: when counting people in computing and other engineering-related careers, people who report their work to be closely related to their engineering degrees, and managers of engineers, 82.7% of BS engineering graduates are using their degrees. Engineers consistently earn more than those with the same levels of education in other fields. Career satisfaction for people with engineering degrees is high, around 90%, regardless of whether they have “engineering” or “non-engineering” jobs. Clearly, most engineers do not use most of the technical content they were exposed to as undergraduates and few people with BS degrees in engineering have stereotypical engineering jobs; paradoxically, engineering degrees are valuable, as shown by self-reported usefulness of the degrees, earnings, and career satisfaction.

**Constraints on ME curriculum**

Vision 2030 and similar efforts give guidance on how engineering programs can meet the objective of preparing engineering students for professional practice. ME curriculum is also subject to constraints: ME curriculum is regulated by ABET and, indirectly, by professional licensure examinations. As noted above, ABET requirements (including the ME program criteria) are so loose that only two courses are specified. Perhaps surprisingly, an ABET-accredited ME program does not even require statics or thermodynamics; ME programs have the liberty to completely reorganize coverage of mechanical and thermal systems to better capture how working engineers operate in these areas. ABET accreditation is not a *de jure* requirement for ME programs; for most programs to be viable, however, ABET accreditation is *de facto* required, as it is seen as a sign of quality and it is, indeed, necessary if graduates are to become licensed Professional Engineers.

ABET Criterion 3 states student outcomes that all engineering programs must address [11]. Although not specific to ME, these outcomes are important for design of ME curriculum not simply for the sake of ABET accreditation but because students should meet these outcomes to be prepared for professional practice. These criteria have evolved over time. In part, in response to industry’s dissatisfaction with the professional skills of graduates—such as skills in communication and navigating corporate and societal contexts—ABET transitioned to outcomes-based education and introduced 11 “a–k” outcomes spanning technical and professional skills [12]. These outcomes are informed by input from industry. Furthermore, a survey of 1,622 employers validates the importance of these outcomes with communication skills being rated as the most important [13]. The student outcomes have subsequently been revised, with the “a–k” outcomes being replaced with 7 new ones. Despite the change in number of
outcomes, because some of the new outcomes are a rephrased combination of the original outcomes, the essence of the outcomes has not greatly shifted. Notably, apart from the discipline-specific program criteria (which are set by societies that are members of ABET), ABET does not specify any technical content.

In the United States, for an engineer to obtain a license, they must have appropriate education (typically an ABET-accredited bachelor’s degree), complete four years of work experience, and pass the Fundamentals of Engineering (FE) and the Principles and Practice of Engineering (PE) exams. Because the FE is taken first, typically around graduation, some programs consider it essential to cover FE content. This stance should be reconsidered in light of evidence on the FE. First, most MEs, probably 75-90%, do not get licensed. Licensure is not required for engineers who meet the “industrial exemption” for those in manufacturing, mining, and telecommunications—most MEs are included in these categories. Furthermore, the first-time pass rate for MEs taking the FE is 79%. Finally, the pass score for the FE is low (probably less than 60%) [14]; also, FE questions are mostly plug-and-chug problems only requiring simple application of content in the FE Reference Handbook, which test-takers have access to during the exam [15]. For these reasons, complete coverage of FE content is not important. A program could strategically eliminate technical content while preparing students who seek licensure to do well enough on the FE to pass. A program could have an “FE track” for interested students while allowing most students to have a greater focus on authentic, practice-based experiences. In summary, the FE specifications are not a serious constraint on ME curriculum, let alone a rigid specification.

Additionally, the FE exam specifications are not evidence of what skills engineers need to have. NCEES states that the FE specifications are drawn not from industry but from a survey of faculty at ABET-accredited programs [16]. In fact, the 2018 content review for the FE was conducted on Survey Monkey with participants recruited with a press release and through the NCEES publication, Licensure Exchange; the survey items on exam content focused on the importance of existing content. Some items did ask whether additional knowledge domains should be added. In any event, the FE specifications reflect the opinions of either faculty or the readers of Licensure Exchange, with neither group being representative of engineers overall. The FE specifications, which address technical content, are in contrast with ABET student outcomes, which reflect the integrated skills that working engineers use.

Summary

What do documents from engineering organizations say about what mechanical engineers need to know? NAE, CFAT, ABET, and ASME all stress an integration of technical skills but say very little about specific technical content. NCEES’s FE exam specifications might be the only document from a national engineering organization that approaches a standard for technical engineering curriculum content but these specifications are not a credible source on what engineers have to know. Looking at the leanness of the ABET program criteria for ME, ASME’s non-participation in the NSPE BOK, and ASME’s statements in Vision 2030, one could characterize ASME’s stance as being that almost no particular technical content matters very much but that it is essential for engineers to be able to solve problems and design things with and for people.
The biggest challenges for mechanical engineering curriculum are not mechanical. There is very little evidence that any given technical topic is not addressed sufficiently in ME curriculum. Vision 2030 led to a loosening of the already flexible ABET program criteria for ME to enable design of curriculum emphasizing open-ended design experiences and development of integrated professional and technical skills. Vision 2030 does identify a deficit in ME graduates’ practical experience and understanding of “how things work and are made.” Aside from those ME-specific issues, ASME’s Vision 2030 fits with the consensus view that engineering education should continue to better prepare engineers who can integrate technical and professional skills.

**Scholarly journal articles**

There are scholarly journal articles that report results of surveys of employers and alumni on which skills are most important for early-career engineers. Most of these articles are not specific to ME. Many of the following articles are discussed in Ref. [17].

Tryggvason et al. report on a major revision of the ME curriculum at the University of Michigan [18]. This revision was informed by a survey taken in 1993 in which alumni rated courses and topics based on their importance; design and creativity, technical communication, interpersonal skills, and professional ethics were rated as the most important; alumni also stated that they were not as well-prepared in these areas as they were in traditional ME technical subjects. The traditional subjects that were the most important were broad math and science as well as computer skills.

A 1993 survey of alumni from Arizona State University shows that alumni (both MEs and all engineering majors) saw communication as being equally or more important than other aspects of their education but that the quality of their instruction in this area was lacking [19]. As indicated by a 1997 survey, engineering alumni of Auburn University were not satisfied with their preparation in communication, computing, and practical design experience [20]. Graduates of Stevens Institute of Technology and their employers, surveyed in 1994–1996 gave high priority to problem-solving, experiments and data analysis, and life-long learning [21]. A survey of recent graduates of a large public university in the Midwest, taken annually from 2000–2006 gave top priority to teamwork, data analysis, problem-solving, and communication [22]; results were similar for ME and for all engineering majors.

In 1999, Richard Felder carried out a survey of graduates of the chemical engineering program at North Carolina State University [23]. Graduates stated that the most valuable features of their undergraduate education were learning problem-solving and time management (from having challenging assignments and from having experience working in teams); stoichiometry was the main technical topic that was seen as valuable. Although these results are from another discipline, they may indicate that much of the value of engineering education is that students are challenged and given experience working in teams.

To help curriculum designers, a 1996 survey of employers in aerospace and defense was conducted by the Industry-University-Government Roundtable for Enhancing Engineering Education showing high importance for “Ability to Structure, Solve, and Report on Solutions in the Engineering Specialty”, data analysis, understanding of ethics and professional responsibility, and life-long learning [24].
Interviews of working engineers can give more details about how they apply these skills. To that end, Jonassen et al. interviewed members of the Missouri Society of Professional Engineers about problem solving [25]. Broadly, in contrast to the problems at the backs of the chapters of most engineering textbooks, workplace problems are complex, have non-technical factors and multiple solutions, and require collaboration and communication; for these reasons, problem-solving skills fostered in undergraduate engineering education are unlikely to transfer to the workplace. Regarding how engineers use mathematical analysis, the authors note,

Our research confirmed that a small minority of workplace engineers regularly use mathematical formulas to represent problems. We are not suggesting that mathematical formulas should not be used in college classrooms, but rather that students supplement them with alternative, qualitative problem representations.

Furthermore, on the topic of what should go into engineering curriculum,

Rarely did practicing engineers recommend more engineering in the engineering curricula. Rather, most of the engineers emphasized more instruction on client interaction, collaboration, making oral presentations, and writing, as well as the ability to deal with ambiguity and complexity.

Taken together, survey and interview data shows the value of broad skills in problem-solving, communication, computing, data analysis, and life-long learning. Even surveys of MEs, specifically, do not reveal any particular technical topics as being of particular significance. These survey findings are in general agreement with the consensus understanding of major engineering organizations.

**Textbooks and handbooks**

Market forces cause handbooks to be evidence of what information is useful for engineers because engineers buy handbooks directly. In contrast, because textbooks are adopted by faculty members, not students or engineers, their contents may be more affected by academic concerns than the practical considerations that engineers face.

With that said, developing innovative, applied, open-ended curriculum that integrates technical and professional skills takes a lot of work. Although the technical content of some textbooks may not be essential, using textbooks helps faculty develop new courses in less time than if starting from scratch; teaching most courses from textbooks enables faculty to put extra effort into a few original courses.

There is also a set of traditional courses that would benefit from moderate departure from textbook coverage due to misalignment with handbooks, which serve engineers in professional practice. Heat transfer and manufacturing are two courses for which this alignment seems particularly poor, such that these courses might be better served with a handbook as a major reference if not the course text; subjects like these are particularly suitable for problem-based learning and the cultivation of technical and professional skills together.

Traditional manufacturing textbooks cover numerous manufacturing processes; some are 40 chapters long with many chapters covering multiple processes. It is hard to imagine an ME job
that requires familiarity with all of these processes. For the sake of specificity, consider sand casting. For this topic, a lot of end-of-chapter problems call for sizing sprues, risers, and shrink rules. None of these calculations is challenging. More substantially, sprues and risers are sized by foundry workers, not mechanical engineers; pattern makers often simply purchase shrink rules. On the other hand, designing parts to be sandcast presents challenging trade-offs between geometry, cost, and performance; for a mechanical engineer to troubleshoot quality problems with sand cast parts, they might have to talk to engineers, metallurgists, pattern makers, and foundry workers.

If they do not size sprues, risers, and shrink rules, what do mechanical engineers do in manufacturing? Handbooks are a valuable source of answers to this question because they are written to serve working engineers. *Design for Economical Production* by Trucks [26] is useful for engineers who design parts because it gives information on how to manage trade-offs between bulk geometry, tolerances and surface finishes, cost, and material properties. It gives enough details that undergraduates can iteratively design parts and specify the processes to make them. In addition to covering processes, *The Manufacturing Engineering Handbook* [27] has whole chapters devoted to Six Sigma, lean manufacturing, operations research, quality, and ergonomics, which are given only a few pages in textbooks if they are mentioned at all.

Issues of alignment between heat transfer textbooks and handbooks are more subtle. Many topics and even formulas in heat transfer textbooks are present in handbooks. When considered in detail, however, the value of textbook coverage is limited due to the lack of consideration of practical factors. For example, common textbooks [28, 29] present mathematical analysis of fins as an application for Fourier’s law of conduction. Textbook analysis shows that triangular or even parabolic tapering of fins leads to optimal heat transfer. (Although this analysis is also presented in some handbooks [30, 31], it is not treated in detail and tapered fins are barely mentioned.) Unfortunately, this mathematical analysis is probably not useful in actual fin design. First, the analysis requires an assumed uniform convection coefficient whereas the convection coefficient is probably not uniform and, moreover, the presence of the fin affects the flow of the surrounding fluid. Fins are often present in arrays; determining how closely to pack fins is difficult because adding fins increases the surface area for convective transfer but it decreases the convection coefficient. Different fin geometries strike different balances between efficiency, weight, manufacturability, and ease of installation. Many fins have geometries that are not easily analyzable mathematically. The value of traditional coverage of fins (to name but one example) is limited because it is presented as an intellectual curiosity in the absence of numerous practical considerations.

On the other hand, some useful, applied topics are absent from heat transfer textbooks; for example, one major application for heat transfer is in HVAC. Although heat transfer is described in textbooks as being a combination of conduction, convection, and radiation, for buildings, heat transfer is described by HVAC engineers as a combination of transmission, infiltration, and ventilation [32]. Transmission calculations account for conductive and convective losses—these calculations are typically done with R-values rather than fundamental application of Fourier’s law of conduction. Infiltration (natural air leakage) is a significant factor and requires accounting for the airtightness of buildings and seasonal variations in wind speed. Buildings need to be ventilated to mitigate things like bacteria, mold, radon, and carbon monoxide; replacing air in
buildings is another contributor to load. Load calculations also have to consider sources of heat, such as people and appliances. Most factors in building load calculations are not mentioned in heat transfer textbooks. Given a chapter from an ASHRAE handbook, undergraduates could do authentic load calculations, a skill more useful and thought-provoking than traditional plug-and-chug convection coefficient calculations.

In summary, textbooks for some traditional ME subjects are misaligned with corresponding handbooks, which is evidence that the traditional content is not essential. Fortunately, handbooks have a wealth of information that can support sophisticated, problem-based design activities that are suitable for undergraduate students. Even if a given student never uses any manufacturing or heat transfer content at work, experience with using handbooks and standards to solve complex problems will serve them well.

**Job advertisements**

The market for engineering talent also aggregates evidence of what engineers are expected to be able to do. One of the easiest ways to identify skills that are in demand is to search sites such as Indeed, Monster, and Career Builder. Here, we will focus on results from Indeed. Table 1 shows the number of jobs for queries for “mechanical engineer” plus a keyword, e.g., “mechanical engineer vibration”. Results will vary regionally so, for illustrative purposes, searches were done for jobs within 100 miles of Wilkes-Barre, Pennsylvania, the home of my institution, King’s College; a narrower search radius would give smaller sample sizes whereas a broader search would be less specific to my region. Data was taken on February 5, 2019.

Job ads can be analyzed quantitatively and qualitatively. The advantage of looking quantitatively at the number of job ads that mention specific keywords is that it is an easy way to get a big-picture view of careers in the field. Table 1 shows that design, communication, and manufacturing are mentioned in half of the ads. Very few technical topics were mentioned in more than a quarter of the job ads. 393 ads mention “license”—from this, one might estimate that about 16% of jobs involve licensure, a minority but still enough that perhaps passing the FE exam should be an explicit goal in the design of some ME curriculum.

Just looking at the number of ads is not enough: reading samples of them is also important. For example, one might see that many job ads mention manufacturing and conclude that their program should have a course in manufacturing and then figure out the content from textbooks. This would be a mistake. In contrast to manufacturing textbooks, which address a large number of manufacturing processes, manufacturing job descriptions often emphasize skills like troubleshooting, supply-chain management, lean manufacturing, and Six Sigma (it is no coincidence that these same topics are mentioned in manufacturing handbooks). Specific manufacturing processes such as machining, casting, sheet metal operations, and forging are mentioned in a small fraction of ads. The obvious difference between manufacturing textbooks and ads mentioning manufacturing means that development of a course on manufacturing should not rely too much on textbook coverage.

To take another example of qualitative analysis of job ads, most ads mentioning “vibrations” are not referring to mathematical analysis but either to vibrations as a job hazard or vibration testing. Some ads mention certification from the Vibration Institute. Such certification is available in
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categories of increasing sophistication, starting mostly with some basic principles and measurement techniques, then fault analysis, development of corrective action, and signal processing and more theoretical treatments of the subject. Those taking vibration certification exams are encouraged to get work experience and required to take specialized training. Because only a few ads mention vibrations, it is probably not necessary to require a course in vibrations; based on reading the ads an elective on the subject should probably emphasize measurement over analysis.

There are limitations to data taken from job advertisements. First, they reflect concerns of employers rather than society so ethics and social responsibility may not be properly weighted. Ads are often written by non-engineers so terms for skills may be used inaccurately and buzzwords may be overused.

Frequency of keywords should not be used alone to justify creation or deletion of courses. For example, although manufacturing is mentioned in most job ads, that frequency alone does not indicate whether it is best to have one required course in manufacturing, a manufacturing-intensive track for interested students, or for content on manufacturing to be present in most ME courses. Some skills might be important but not expected of early-career engineers; e.g., simply being able to explain the philosophy of lean manufacturing might be enough for a new graduate. And, again, there are mismatches between terminology used in job advertisements and textbook content—vibrations is a notable example—so qualitative analysis of job advertisements should be used to confirm course content. Conversely, technical knowledge might simply be assumed; despite being foundational to some key skills, calculus, differential equations, statics, and thermodynamics are barely mentioned.

**Working Engineers and Industrial Advisory Boards**

Individual working engineers are often willing to share their insights and experiences if asked by curious faculty members. They can offer general opinions on the relevance of course content but their opinions are naturally influenced by the field they work in and the functions they perform; just because one engineer uses root locus does not mean that all MEs need to learn it. Talking with individual engineers is especially helpful when developing authentic, practice-based experiences: they can share problems that they have had to solve and point out relevant sources of information. For example, a working ME could describe how they selected a cooling tower and point out relevant theories, factors to consider, handbooks, standards, and catalogs from which a paper design project could be developed. Although most MEs will never select a cooling tower, doing so as a class project would cultivate integrated design, technical, and professional skills that would benefit every student.

Going beyond discussion with individual engineers, almost all engineering programs have industrial advisory boards (IABs), members of industry who meet periodically to help the program. A survey has been done of directors and members of IABs [33]; other than that, not much systematic research has been done on what makes these boards effective. The survey data shows that IAB members believe that contributing to curriculum is important but that their influence is not always as effective as they would find suitable. IAB members can contribute to things beyond ABET accreditation and curriculum development, such as engaging with students.
and advocating for the program. Because of the credibility held by IAB members, their role can go beyond simply giving information on curriculum to advocating for curriculum revision to not just faculty but students and administration, as well.

IAB members can contribute to curriculum beyond participation in regular IAB meetings; for example, they can be guest speakers in classes or run workshops on special topics, developing capstone projects, and sharing materials from training taken by working engineers [34]. Vision 2030 calls for a “new balance of faculty skills” [3]. incorporating engineers with extensive industrial experience as professors of the practice; IAB members may be suitable candidates for these roles.

Conclusions

The best mechanical engineering curriculum is the right one at the time for an individual institution’s students and the people those students will go on to serve. The background of students, institutional mission and resources, and industry needs should all influence curriculum design. Programs where graduates stay close can more precisely prepare them for particular regional or even local industry needs. The sources of evidence discussed in this paper—reports from organizations, scholarly journal articles, textbooks, handbooks, job advertisements, and industrial advisory boards—are applicable to some degree to all ME programs but should be relied upon in different ways for each individual program.

With that said, over the past couple of decades, findings from organizations such as ASME, ABET, CFAT, and NAE, as well as numerous peer-reviewed papers, point to the need for more rigorous development of integrated technical and professional skills and more authentic experiences for undergraduates. Even so, most ME curricula have not changed in response to that consensus view. Furthermore, ME curricula are still mostly structured around a core of six engineering sciences, as advocated for without evidence by the Grinter report more than 60 years ago [1]. On the other hand, the Grinter report noted evidence at the time that engineering students had underdeveloped communication skills and background in the humanities and social sciences—those concerns are still relevant today. The challenges for design of ME curriculum are not tied to technical ME curricular content.

The 2009 NSF 5XME workshop, Vision 2030 [3], and Educating Engineers [9] all advocate the development of a professional or design spine, a set of courses across the curriculum in which students cumulatively develop professional skills. This design spine is in contrast to the traditional ME curriculum model, which revolves around development of technical understanding in engineering sciences, mainly mechanics and thermo/fluids.

Obstacles to implementing a design spine include determining what content to include in it and how to eliminate content elsewhere to make room for the design spine. Although it is appealing to have continuity across the design spine, integration of technical and professional skill development within a single course is already challenging. Cutting courses altogether may raise fears, rightly or wrongly, that students are underprepared technically or may be unable to obtain licensure. Combining courses, such as fluid mechanics and heat transfer, could lead to content being presented rapidly without depth and may require students to purchase multiple textbooks
for a single course. For practical reasons such as these, one reasonable path toward implementing a design spine is to revise traditional courses to have more design content.

Mechanical design is an ME course that traditionally integrates some engineering science and design content. Depending on the instructor, the course could focus more on advanced solid mechanics theory or plug-and-chug formulas for calculating, e.g., wear on gear teeth. However, many mechanical design courses are taught with more practical content (e.g., selecting gears from a real catalog), integration of theory and detail design (e.g., combining theory for stresses in beams, fatigue, and stress concentration for iterative design of a shaft), and culminate in a design project in which students translate specifications into a parts list and drawings (e.g., design of a gear box with shafts and bearings).

A few other common ME courses can be structured similarly. Understanding how things are made is cited as a weakness of ME graduates. However, teaching manufacturing by progressing steadily through a textbook would lead to broad and shallow content coverage. Another approach would be to consider how MEs make decisions about how to make things, perhaps focusing on a class of materials such as metals. Processes could be connected by relating the bulk geometries and tolerances they can achieve, their effects on material properties, and their costs. Making these comparisons enables teaching students to iteratively select a process for a part to design the part to accommodate the constraints of the processes. Manufacturing handbooks (e.g., Refs. [26, 27]), standards, material catalogs, and online cost calculators are available to support this instructional strategy. Some processes are naturally linked sequentially (such as casting, machining, heat treating, and coating) which can lead to design of a manufacturing system in a factory and then consideration of how people in that factory would need to work together to achieve efficiency and quality. Skills in lean and Six Sigma are in demand but these topics are difficult to learn without an understanding of how things are made through a sequence of steps. In short, manufacturing courses can be re-oriented from presenting content about a range of processes to focusing on how engineers make decisions; such an approach would give students more practice with design, decision-making, and information literacy which would even benefit students who do not eventually work in manufacturing.

Heat and mass transfer is one of Grinter’s six engineering sciences but this subject is perhaps better taught from a design than an engineering science approach. Some fundamentals could be highlighted, perhaps by focusing on how the main concepts can be used for estimation. More detailed topics may be better addressed in a problem-based format. For example, rather than covering every empirical correlation for convection in the book, enough empirical correlations will naturally arise as students design heat exchangers. Heat exchanger design requires managing a range of trade-offs: increasing heat exchanger efficiency also increases fluid pressure losses, more complex geometries might be more efficient but also more expensive, and so on. By working on such a project, students would be able to use technical content from other courses such as fluid mechanics and manufacturing; more substantially, students would need to link communication, life-long learning, engineering science, and design—a closer approximation of professional practice than is afforded by most textbook problems. Other topics such as radiative heat transfer and conduction in complex geometries may also be better addressed by projects employing the tools that working engineers use such as handbooks, catalogs, and computer simulations. As mentioned previously, using an ASHRAE handbook to do load calculations on a
building is a straightforward, challenging, and meaningful way to introduce students to a major application of heat transfer.

In summary, the evidence supports shifting from a focus on engineering science to teaching engineers who are practical thinkers and can employ technical and professional skills in tandem. Experience with technical topics is more important than which exact technical topics are covered, given that most MEs do not use most of the technical content they learn in school and many do need to learn new technical content at work, anyway. In comparison with teaching traditional technical content, teaching integrated technical and professional skills is challenging due to the relative lack of instructional materials; a design spine may be a good model in principle but making one from scratch is challenging. One reasonable strategy for giving practical experience and developing professional skills is to focus on revising several individual courses to model how working engineers do their work in these areas; this mode of instruction is supported by resources such as handbooks, standards, and catalogs and all but requires the use of skills for life-long learning, professional decision making, and communication. A design spine could then be implemented by integrating professional skill development across courses.

References


