# Integrated Engineering Curricula

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## ABSTRACT

**Increasing emphasis on interdisciplinary research and education requires researchers and learners to build links between distinct disciplines. In engineering education, work on integrated curricula to help learners build connections between topics began with three programs in 1988. Integrated curricula have connections to a larger movement in higher education—learning communities, which help learners to build interdisciplinary links and social links within a community. Integrated engineering curricula have provided concrete assessment data on retention and student performance to augment research on learning communities. While innovators in both movements have offered many prototypes and gathered many data, goals and results from programs implemented to date are not sufficiently well defined to guide the design and implementation of programs at other institutions. This paper discusses the importance of integration, reviews accomplishments to date, draws conclusions by analyzing those accomplishments, and suggests future initiatives.**

## I. INTRODUCTION

Today, engineering curricula have solid foundations in science and mathematics, with the expectation that students connect mathematical and scientific concepts to engineering practice, i.e., design and modeling. Several reasons suggest, however, that the relationships among mathematics, engineering, and science have not been clearly communicated through science-based engineering curricula. First, undesirably low percentages of engineering students remaining in engineering one year after matriculation have inspired first-year engineering courses that improve retention by making explicit connections to engineering, engineering practice, and engineering careers that could not be accomplished with student exposure to only mathematics and science courses [1, 2]. Second, comments from students suggest that they see few connections between their mathematics and science courses and their future careers in engineering. Comments like the ones from two mechanical engineering students at the University of California Berkeley echo through the halls of engineering buildings on every campus:

> "Well, mathematics is, basically…abstract…unless you apply it to something, you don't have a physical foundation… It's more conceptual, you have to be able to manipulate symbols…You got to get over the fact that it may seem pointless, and just do it. That's probably one of the hardest things in math, that there's no reward, there's no tangible physical thing that you have. You didn't find out how far this ball is going to fly, or how long it will take for this thing to cool down. You have a number, and you can't do anything with this number."
>
> "The problems in math have absolutely no significance at all. It's purely an exercise" [134].

Third, engineering faculty members indicate that students should be better able to apply introductory science and mathematics in their engineering courses. Robert Kowalczyk, a professor of mathematics at the University of Massachusetts Dartmouth, states that "engineering had a pretty high dropout rate, and the students who made it through were doing okay, but not as well as we would expect. So this gave us a chance to look for other pedagogical techniques that could help us retain the students as well as do a better job teaching them" [171]. Together, these reasons suggest that students need to make better connections among and within mathematics, science, and engineering to perceive mutual relevance and apply concepts and ideas from one subject area to tasks in another.

Recognizing the opportunity, several institutions initiated programs to help students make more and stronger connections among mathematics, science, and engineering (and sometimes other subject areas). These initiatives are frequently described as integrated curricula. Most initiatives began as pilot programs for a fraction of an institution's engineering students, and some were expanded to implement a renewed curriculum for all engineering students. While integrated curricula proceeded in engineering, programs to develop academic and social connections were initiated as learning communities [135, 136]. Almost every integrated curriculum initiative could be classified as a learning community, placing integrated curricular initiatives within the larger context of learning communities. While the literature contains both descriptions of individual integrated curricular initiatives and summaries of multiple efforts, synthesizing what has been learned collectively from the many initiatives remains an important task to guide future research. This paper achieves a more thorough fusion of the work on integrated curricula, makes connections to what is known about learning communities, and suggests avenues for future research and innovation.

To accomplish these goals, the paper addresses the following questions in separate sections:

- What is integration? What theoretical foundations motivate the need for integration?
- What are the characteristics of integrated curricula programs that have been offered for first-year engineering students? How might the results of these programs be viewed?

- What are the characteristics of integrated curricula programs that have been offered in engineering science? How might the results of these programs be viewed?
- What might be learned from the integrated curricular programs offered to date?
- What are potential avenues for future research?

## II. Background/Motivation

If a curriculum is revised using engineering principles, a pilot initiative should establish learning goals based on a rationale that reflects beliefs, theories, and assumptions about engineering practice, educational goals, and learning [137, 138]. Learning outcomes and/or objectives should be derived from these goals. Assessment processes related to each outcome/objective would be developed and data collected. Learning activities would be designed to facilitate desired learning. The degree to which each initiative followed this process varied, yet the described process contains elements common to all the initiatives. This section presents three driving forces in the development of integrated curricula: integrative and reductive educational goals, the science of learning, and diversity. Finally, we distinguish the programs and curricula studied in this paper from the broad use of the term "integrated" in the engineering education literature.

### A. Integrative plus Reductive Educational Goals

The engineering approach, defined by Koen [139] as "the strategy for causing the best change in a poorly understood situation within available resources," links concepts and resources together "to create what has never been" [31]. Given the integrative nature of engineering, authors [31, 141, 142] and national studies of engineering education [3–7] have argued that engineering curricula should promote integrative, synthetic thought processes as well as reductive, analytical processes.

> "The ability to make connections among seemingly disparate discoveries, events, and trends and to integrate them in ways that benefit the world community will be the hallmark of modern leaders. They must be skilled at synthesis as well as analysis, and they must be technologically astute. Within university communities, in particular, we must create an intellectual environment where students can develop an awareness of the impact of emerging technologies, an appreciation of engineering as an integral process of societal change, and an acceptance of responsibility for civilization's progress" [31].

Integrative thought processes have been presented as an educational goal, worthy of standing alone, and as a necessary counterbalance to what has been portrayed as a near universal emphasis on understanding via decomposition.

> "The need to create sound syntheses and systemizations of knowledge…will call out a kind of scientific genius which hitherto has existed only as an aberration: the genius for integration. Of necessity this means specialization, as all creative effort does, but this time, the (person) will be specializing in the construction of the whole. The momentum which impels investigation to dissociate indefinitely into particular problems, the pulverization of research, makes necessary a compensative control—as in any healthy organization—which is to be furnished by a force pulling in the opposite direction, constraining centrifugal science into a wholesome organization…the selection of professors will depend not on their rank as investigators but on their talent for synthesis" [142].

Calls for an integrative approach to complex systems are also motivated by research in other disciplines because important observations that emerge from studies of these systems cannot be explained using only reductionism. British Telecom's design of software to manage communications networks modeled after ant colonies is one example:

> "The idea is to send out 'ants' or intelligent agents, to explore alternate routes through the network. Each ant returns, almost instantly, with information on how long it took to travel between different parts of the network. With information from thousands of ants, the network can reconfigure itself to bypass the problem in less than a second—far faster than the several minutes BT typically needs now for the same task" [143].

Biologically motivated algorithms now form substantive research thrusts in distributed intelligence [144, 145]. Studies of these and other complex systems show that researchers and practitioners must join work from disparate fields to construct solutions.

### B. Science of Learning

The science of learning has offered another set of reasons for promoting integration. First, studies of experts and novices have shown that, as expected, experts have a larger factual knowledge base than novices. However, the studies have also shown that expert knowledge is richly structured to "facilitate retrieval and application" [146]. To become experts, students must not only acquire facts, but also organize their knowledge to facilitate its application to diverse situations. Neurological studies of how the brain functions on a biological level also note the importance of the structure of knowledge [147]. Functional magnetic resonance imaging (fMRI) studies have indicated that people need to make connections between their existing knowledge and a new word or image in order to remember that new word or image [148, 149]. Faculty members often implicitly present reasons for integration as they repeatedly call for students to *understand* the material. While understanding may not be observable, Svinicki argues that attributes frequently ascribed to understanding also characterize structured knowledge [150]. Further, ways in which students have structured their knowledge might be assessed through tools such as concept maps [151–153] or through exercises in which students organize, relate, or classify information.

Questions have been repeatedly raised about whether neatly compartmentalized courses can provide learning activities that stimulate, encourage, and enable students to structure their knowledge across course and disciplinary boundaries. Engineering curricula require mathematics and science courses because engineering faculty members expect that students will be able to transfer what they learn to engineering courses. Although transfer was anticipated when engineering curricula were designed, conversations among engineering faculty members suggest that the desired transfer is not occurring to a sufficient degree [171]. Transfer is a laudable learning goal, yet

research has suggested that enhancing transfer is difficult [154–156]. Learning environments that emphasize connections among subject areas might enhance the degree to which students would be able to transfer their knowledge to engineering courses.

### C. Diversity

Based on research related to underrepresented groups in engineering, integrative programs should appeal to a broader audience. Rosser [157] reported differences between how men and women approach problems. Men tend to be more comfortable with problems having a single correct or concrete answer, while women are better able to deal with problems that are complex or ambiguous. Rosser asserts that many of the first-year courses focus on concrete problems, favoring the learning style of men. Rosser asserts that this is one of the reasons women (even those with high GPAs) leave the major in the first year.

Since Tinto has found that learning communities are an effective way to encourage students to affiliate—and affiliation leads to improved persistence, particularly among women and minorities [158]—we should anticipate that integrated curricular programs that develop communities of learning will create improvements in retention rates as an outcome. This would be a valuable discovery in that traditional learning communities, many of which feature a shared residence, are not common components of minority engineering programs [159].

### D. How the Engineering Education Community Defines Integration

Integration has been used to characterize diverse initiatives. A survey of titles in the proceedings of the 2003 American Society for Engineering Education (ASEE) annual conference found that the words "integration," "integrate," "integrating," and "integrated" appeared in forty-one paper titles. Nineteen of these papers—nearly half—addressed integrating a thread of a particular nontechnical subject into an otherwise unchanged engineering course or curriculum, including business, communication, ethics, culture, and sustainability. Of these, collaborations between engineering and business are the most common and have potential as a subject for further study. Another paper addressed incorporating nontechnical subjects as preparation for accreditation.

Another twelve papers addressed integrating new technical coverage into the engineering curriculum, enhancing disciplinary-specific outcomes. The most common was integrating into biology into biosystems, chemical, and environmental engineering curricula. Alternatives ranged from simply adding biology coursework to a more threaded approach that integrates biology throughout the curriculum. Others in this category included engineering economics, graphics, design, statistics, and computer skills such as programming, numerical methods, and simulation.

Other papers described integration of engineering topics or objectives into teacher education and architecture courses. Some faculty members certainly integrate engineering materials into courses taught outside engineering to improve engineering student outcomes, but no work of this nature was reported in the papers sampled. However, there was a paper on building academic and social connections through a national project competition.

Five other papers described the holistic integration of engineering fundamentals in programs at Michigan Tech, Texas A&M-Kingsville, NC State, Florida, and James Madison. Two additional papers described the integration of curriculum material in more advanced courses and an entire degree program.

Approximately twenty papers (beyond the forty-one considered) were not classified because the word "integrated" was used in an entirely different sense to mean "incorporated" or in special cases such as "integrated circuit." For this paper, integrated curricular projects are studied only if they satisfy each of the following criteria.

- Faculty members from multiple disciplines collaborate(d) in developing and implementing the curricula. This excludes the incorporation of material from other disciplines into courses by faculty members from a single discipline, the incorporation of tools into courses by faculty members from a single discipline, and capstone design projects restricted to a single discipline.
- Projects must report assessment data to ascertain the degree to which a project has affected some student outcome (e.g., retention or performance).
- Students in the program must enroll in courses from different disciplines (e.g., engineering and physics) or enroll in a course that combines courses from multiple disciplines.

## III. Common Themes in Freshman Integration Efforts

Using the criteria in the previous section, several first-year integrated programs [13–113] were analyzed to identify common themes. They are presented in the following nine subsections. These themes establish a pattern of the experience of the engineering education community with such programs, guiding both program implementation and future research. Differences among programs (pointed out within each subsection) address the range of applicability of integrated programs. A table summarizing these programs was too large to include here but is available online [163]. The following subsections address experiences and data related to:

- student learning of disciplinary engineering content;
- student learning of nondisciplinary skills, often referred to as "soft skills," more recently reflected in the engineering criteria developed by ABET;
- increasing the number of engineering graduates by improving retention;
- the success of integrated programs in addressing the needs of underrepresented groups;
- student workload issues related to the implementation of integrated curricula;
- the process and dynamics of institutionalization, including the use of pilot programs;
- the establishment and nurturing of faculty collaboration;
- the use of design projects as an integrative learning activity; and
- the dynamics of developing social and academic connections.

### A. Improving Student Disciplinary Learning

Improvements in student learning of disciplinary engineering content were estimated primarily using grades and grade point averages (GPAs). Some researchers have used normed tests where an appropriate instrument was available. Differences in how programs collected and analysed GPAs prohibit the analytical comparison of the different results. In general, students who participated in pilot

programs earned higher GPAs than students in comparison groups, yet there were differences in whether the higher GPAs were earned in the first year, downstream courses, or cumulatively. In a small number of programs, faculty members used scores on common examinations to estimate differences in student learning.

Students in the Freshman Integrated Program in Engineering (FIPE) pilot at Arizona State University (ASU) earned scores that averaged 30 percent above those of traditionally taught students on the Force Concept Inventory (FCI) [17]. On scale-up, there was a statistically significant reduction in class grade performance, although the researchers refer to the grade difference as "close" [18]. Students in Drexel's Enhanced Educational Experience for Engineers ($E^4$) had higher GPAs than students in the traditional curriculum [30]. Studying the 1993 through 1996 cohorts of students in the Integrated First-Year Curriculum in Science, Engineering, and Mathematics (IFYCSEM) at Rose-Hulman Institute of Technology, researchers found no difference between the cumulative GPA of participants and nonparticipants. Studying quarterly GPAs and rates of retention, IFYCSEM students do better at the sophomore level than matched comparison and traditional groups [62]. More recent data indicate that the gap between IFYCSEM cohorts and the comparison group widens as students progress in the curriculum [59]. Preliminary data from the University of Pittsburgh confirm the School of Engineering's success with the new approach. According to Budny, "not only are [the students'] grades up, but [they] are retaining more of the information they've learned, almost to the point that they are on the level of students in the Honors College" [113]. At Louisiana Tech, Nelson and Napper reported that the fraction of integrated program students receiving successful grades (C or better) exceeded that of students in the traditional curriculum in multiple classes in the 1997–98 year—69 percent vs. 63 percent in Pre-calculus, 92 percent vs. 49 percent in Calculus I, 95 percent vs. 37 percent in Calculus II, 85 percent vs. 62 percent in Chemistry I, 96 percent vs. 64 percent in Chemistry II, and 87 percent vs. 76 percent in Physics I. Similar results followed in the 1998–99 academic year [43].

Students in the Integrated Mathematics, Physics, and Engineering Curriculum (IMPEC) at North Carolina State University had significantly higher pass rates (C or better) in core courses (69 percent IMPEC / 52 percent comparison group/ 52 percent all students taking E100, NC State's introductory engineering class). IMPEC researchers found roughly 80 percent of both the IMPEC and comparison group remained declared engineering majors one year later, but fewer IMPEC students were in academic difficulty. IMPEC students did as well as or better than comparison students on common final examination questions in calculus, chemistry, and physics courses. The IMPEC students also did well on questions that tested them for deeper levels of comprehension of principles that were among the principal objectives of IMPEC. (There was no way of including such questions on the final examinations in the traditionally taught courses.) IMPEC students' performance on the FCI was substantially better than the average performance of students at other institutions who had taken a traditionally taught lecture-based mechanics course [14, 44]. The IMPEC students slightly increased their confidence in their calculus ability in the first semester (a predictor of academic success). The E100 students maintained but did not increase their confidence, and the confidence of the comparison group declined sharply. The IMPEC students' confidence in physics increased slightly in the first semester, which is interesting since none of them took a physics course that semester. Their increased confidence in certain areas may have made them more confident in general, or the emphasis on applications in the Harvard Calculus approach may have increased their confidence in their ability to deal with physics problems. Their confidence in physics increased sharply after they took the physics course in the second semester.

Logistical difficulties forced Knowledge Studio participants at the University of Florida to take a common exam with other sections of calculus and chemistry. The format of the common exam was different from the tests administered throughout the integrated curriculum, and the students in the pilot curriculum did not perform as well as students in the traditional curriculum who were better prepared for the common exam [14]. However, at the completion of the two-year program, multiple regression showed Knowledge Studio GPAs in mathematics were significantly higher than those of the control group, Knowledge Studio GPAs in chemistry were significantly lower, and Knowledge Studio and control group overall GPAs and GPAs in physics were not significantly different.

Faculty members at the University of Massachusetts Dartmouth evaluated student learning in calculus by giving a common calculus examination to students in the Integrated Mathematics, Physics, Undergraduate Laboratory Sciences, and Engineering (IMPULSE) program. Students in the pilot (1998–99) scored 77 percent (vs. 62 percent in a comparison group), while students in the 1999–2000 program offered to all calculus-ready engineering students scored 77 percent. In addition, higher percentages of IMPULSE students completed the calculus course (96 percent vs. 72 percent), a completion rate matched (95 percent) by the full implementation in 1999-2000 [112].

### B. Seeking Nontechnical Outcomes: Foreshadowing ABET EC2000

Integrated engineering curricula were developed at Drexel, Texas A&M, and Rose-Hulman in response to several significant reports on engineering education, all released in the same time frame [3–7]. All these reports emphasized the importance of nontechnical outcomes and characterized the traditional system of engineering education as being overburdened and inflexible. These nondisciplinary skills formed a common set of outcomes that foreshadowed those eventually required for accreditation by ABET's EC2000—the ability to function on multidisciplinary teams, an understanding of professional and ethical responsibility, an ability to communicate effectively, the broad education necessary to understand the impact of engineering solutions in a global and societal context, a recognition of the need for and an ability to engage in life-long learning, and a knowledge of contemporary issues [164]. It was expected that integrated curricula could achieve these outcomes in a way that no other approach could. Valentine and colleagues point out, however, the conundrum of assessing integrated curricula—its innovative nature defies standard quantitative measurements—and report that attempts to demonstrate observable differences in nondisciplinary skills between students in integrated curricular pilots and students in comparison groups have not generally shown any differences [38].

Student journals were used to assess communications skills in $E^4$ at Drexel [30, 38] and by Ostheimer and colleagues [141]. Student self-report surveys were another common way to assess these outcomes. To a much greater extent than students in the regular freshman engineering course, IMPEC students credited their

engineering course with helping them improve their skills in problem solving, studying, teamwork, time management, reading, writing, speaking, and computing. The IMPEC students' self-rated confidence in their abilities in chemistry, engineering, computing, speaking, and writing increased sharply in the first semester. The confidence levels of a comparison group declined (dramatically in chemistry and writing, slightly in engineering, computing, and speaking). The confidence levels of students of the entire cohort of E100 students either declined sharply (in chemistry), stayed roughly the same (in engineering), or increased slightly (in computing, speaking, and writing) [14]. The Connections program at the Colorado School of Mines (CSM) sought to integrate societal, historical, and ethical contexts and to improve students' communication skills, but reported no assessment of these outcomes [27]. A special instrument was designed to assess a broad set of nondisciplinary skills of participants in an integrated first-year curriculum at the University of Alabama, but faculty members did not observe a difference between integrated and comparison groups [103].

### C. Retaining Students in Engineering

Many engineering education interventions focus on the retention of students in engineering. As described in the background material, section II, helping students make connections between their first-year subjects and engineering practice, as well as fostering social connections among students should improve retention. Improvements were observed in several pilot programs, yet Richardson and Dantzler raise a reasonable concern that improved retention might be explained by the fact that most pilot programs recruited volunteer participants [104].

For the Gateway program's first-year curriculum at Ohio State University, participants were retained in engineering at rates of 85–90 percent compared to 70 percent for a matched comparison group. Students in the pre-calculus program were also retained at a higher rate than a comparison group (46 percent vs. 26 percent) [81]. Students in Drexel's $E^4$ had higher retention and made faster progress than counterparts in the traditional curriculum [30]. The retention rate of students in Alabama's first-year integrated program was 20 percent higher than that of students in the traditional curriculum, and interest increased. Student motivation was markedly greater than among those who attended the traditionally designed alternative [101]. Engineering students in Embry-Riddle's Integrated Curriculum in Engineering (ICE) program had retention rates 13 percent above those of a comparison group by the eighth semester [42].

A longitudinal study of the Connections program by Olds and Miller showed that participants graduated at a higher rate than other freshman students entering CSM. The difference is greatest (and statistically significant) for the second (1995–96) cohort, in which 84 percent of Connections participants graduated within six years, compared to only 60 percent of the CSM cohort [26]. Tracking students from the first three years of IMPEC, Felder and colleagues anticipated a higher retention rate compared with the average for the entire freshman class [44]. A later study showed no difference between the IMPEC students and a matched comparison group [14].

Since student attitudes regarding engineering strongly influence whether they will be retained, survey data of student perceptions are frequently used, especially as an early indicator. At NC State, all first-year students (IMPEC, comparison, and E100 groups) strongly agreed with the statement "I expect engineering will be a rewarding career" at the beginning of the fall semester. Some decline is to be expected during the first semester, as students learn more about engineering and some find that they are poorly suited to it. At the end of the semester, the average level of agreement for the control and E100 groups declined two to four times more than that of the IMPEC students, which declined only slightly. In addition, the IMPEC students' level of agreement with the statement "The engineering course helped me know whether I want to major in engineering" was significantly greater than that of the comparison and E100 groups.

At the completion of the two-year Knowledge Studio program at the University of Florida, a higher percentage of participants was still in engineering than a comparison group (60 percent to 50 percent), but this difference was not statistically significant. Knowledge Studio students were observed to be less likely to withdraw from a course and less likely to fail a course, yet neither difference was statistically significant. Similarly, an improvement in graduation rates (57 percent vs. 49 percent) was not significant [14].

Texas A&M University investigators have studied the time students take to complete the curriculum required for entry into a specific engineering major at the sophomore level and report that, since cohorting programs were institutionalized in 1998, clustered students have progressed through the required courses more quickly than students who, for many different reasons, participate in nonclustered cohorts (3.6 vs. 4.1 semesters for 1998 and 1999 freshmen) [77].

Overall, Foundation Coalition schools have seen 10–25 percent increases in the retention rates of first-year engineering students and, in many cases, even greater improvements in the retention of women and underrepresented minorities [79].

### D. Promoting Diversity

Since integrative programs should appeal to a more diverse audience (see section II), some integrated programs have sought to attract and retain a more demographically diverse student body within the engineering disciplines. Specifically, women and minorities have historically been underrepresented among engineering graduates because of low admission numbers in the first year and high rates of attrition in both groups [8].

Data from the 1994–95 academic year at Texas A&M, when the integrated first-year pilot program was first offered, show a 72 percent retention rate among women engineering students who participated in the Foundation Coalition (FC) program, compared to 66 percent among women engineering students who were not involved in the FC program. With regard to underrepresented minorities, fully 95 percent who participated in the FC engineering program were retained, compared to 66 percent of the minorities who enrolled in the conventional engineering curriculum at Texas A&M [8]. $E^4$ students were also found to have higher rates of retention and progress, particularly among women and minorities, and to have GPAs that were superior to those of their counterparts in the traditional program [30].

Yamamoto collected data using the FCI to compare the quality of the IFYCSEM program with that of the conventional curriculum at Rose-Hulman [61]. The gain between pre-test and post-test for both groups was analyzed and evaluated in light of pre-admission SAT scores and gender. While the performance of all students in the IFYCSEM program improved slightly more than that of the students in the conventional curriculum, the performance of female students in the IFYCSEM program improved significantly more than that of the female students in the conventional curriculum. This difference may be explained in part by significant differences

that were found between male and female students in the amount of time spent studying. Women students reported an average of sixteen to twenty hours of study time per week, whereas the men spent an average of eleven and fifteen hours of weekly study time [62].

Five years following their admission in the fall of 1994 and 1995, the graduation rates of Connections participants were higher for both males (72 percent vs. 55 percent for the 1994 cohort, 81 percent vs. 59 percent for the 1995 cohort) and females (81 percent vs. 59 percent for the 1994 cohort, 90 percent vs. 64 percent for the 1995 cohort) than for students in the remaining CSM cohort [27]. Results from the University of Florida's Knowledge Studio do not fit with these results. A significant difference existed between the Knowledge Studio and comparison groups for males (66.7 percent to 53.0 percent), but the difference for females (39.2 percent to 38.6 percent) was not significant. No differences were observed between racial minority/majority groupings [14].

If underrepresented groups, particularly minorities, are to be able to take advantage of the benefits of integrated curricula, those curricula must be designed to be accessible to students who are not calculus-ready. At the University of Alabama, incoming freshmen who declare an interest in any engineering discipline are required to take a university math-placement exam prior to admission. Students who are not calculus-ready enroll in a pre-engineering course [105]. Ohio State's Gateway curriculum originally served only students who were calculus-ready, but a companion curriculum was developed the following year (1994) for students starting in pre-calculus [81]. Nelson and Napper indicate that the majority of students enrolling in engineering programs at Louisiana Tech University are not calculus-ready [43], so faculty members use just-in-time delivery—reviewing specific pre-calculus topics just prior to the point in the course where knowledge of the topic will be needed to understand a calculus concept. In this way, both pre-calculus and calculus topics are covered in first-year engineering math [43].

### E. Student Workload

Drexel's $E^4$ curriculum boasts as one of its positive outcomes "a ten-fold increase in the number of hours devoted to engineering in the first year" [33]. In today's climate, when legislatures and governing boards are trying to reduce the number of hours required in degree programs, this might not be such a popular claim, even though it is based on starting with a very small number. Because integrated curricula are intentionally designed to broaden the set of outcomes expected of students, they risk creating a larger workload for students. Cordes and his colleagues felt that their first offering of the integrated computing curriculum had attempted to pack too much material into too short a time frame [100]. Consequently, they recommend that, rather than attempting to teach programming, digital logic, and relevant discrete mathematics in one semester, discrete mathematics should instead be used initially to guide the introduction of other topics [100]. Of students in IFYCSEM at Rose-Hulman, 63.3 percent indicated that the course material was too "heavy," and 42 percent reported that the course material was presented too fast [62]. The positive attitudes of the IMPEC students to almost every aspect of the course are all the more impressive considering that they found the curriculum more demanding than the matched comparison and E100 groups found their first-year curricula (as evidenced by their responses to certain questions on the Pittsburgh Freshman Engineering Attitude Survey) [14].

### F. Scaling Up

As is common in the introduction of significant curricular change, nearly all first-year integrated curricula start out as pilot programs. Colorado School of Mines accepted forty-nine of 299 academically eligible students into its Connections program [26]. Drexel's $E^4$ first served 100 (of 600) engineering freshmen in 1990 and promoted the growth of $E^4$ by tripling the size of the program's laboratory facilities in 1993 and expanded the program to include all engineering freshmen in fall 1994 [41]. The first implementation of FIPE at Arizona State in fall 1994 was delivered to thirty-one students [17], and IMPEC was piloted for thirty-six students in 1994. The program size remained constant until components of IMPEC were absorbed into a new offering serving the entire freshman class [14]. The University of Alabama's first integrated curriculum pilot initially served thirty-six students [92]. For its second-generation effort for all engineering majors, it began with 40 percent of the 400 (160 students) entering engineering students [79].

Louisiana Tech implemented a pilot integrated freshman curriculum in the fall of 1997 that enrolled forty students. The following year, 120 new students began the program, which was fully implemented in the 1999–2000 school year [43]. The University of Pittsburgh's pilot integrated program was so successful that it is now being implemented throughout the School of Engineering, the Mathematics Department, and in select science classes [113]. The Texas A&M clustering program proved to be so successful that it was expanded to include all freshmen in 1998 [75].

There is also a pattern of implementing a compromise that includes some, but not all, of the features of pilot integrated programs. Systemic resistance to implementing the Gateway program for all engineering students was addressed by developing a two-quarter sequence titled "Introduction to Engineering" based on the lessons of the integrated program [81]. Similarly, parts of NC State's IMPEC were incorporated into the NC State freshman program [14]. As the examples of Ohio State's Gateway curriculum and curricula across the Foundation Coalition show, positive outcomes to learning and retention are not sufficient to cause institutionalization [11].

### G. Faculty Collaboration

Communication and collaboration among faculty members from different disciplines are required to design, implement, and sustain an integrated curriculum. Many faculty members viewed the additional time required for ongoing communication as above and beyond the amount of time they were willing to commit to teaching a first-year course. Faculty collaboration, however, is critical to establishing cross-disciplinary connections. It is through this collaboration that faculty can model cross-disciplinary partnerships in which students are expected to practice, identify connections to share in the classroom, and build a community of learning that will set the program apart from traditional instruction. It is important that collaboration with faculty members from other disciplines be founded on an equal partnership in which all faculty members have the chance to contribute and benefit.

Programs are diverse as to the disciplines of participating faculty. Drexel $E^4$ faculty members came from thirteen different departments, including humanities, arts, sciences, and engineering [30]. Other programs featured collaborations of engineering with math and physics (Ohio State [81] and UC Berkeley [134]), physics, math, and English (Arizona State [17]), math, physics, chemistry, and English (University of Massachusetts Dartmouth [107]), math, physics, computer science, and chemistry (Rose-Hulman

[59]), math, physics, and chemistry (University of Alabama [92]), NC State [44], University of Florida [14]), and humanities, social sciences, chemistry, geology, physics biology, and mathematics (University of Pittsburgh [113]).

The level of faculty collaboration commonly goes far beyond simply teaching the same cohort of students. At the University of Alabama, investigators met two to four hours a week during the academic year to generate topics and examine opportunities for integration [92]. They found particular challenges in integrating mathematics and chemistry, since most freshman-level chemistry courses involve algebra-based math and require little or no calculus. In contrast, Izatt and colleagues at Alabama found that integrating chemistry and physics went more smoothly [96]. Similarly, groups of Arizona State faculty members brainstormed to identify connections among subjects [17, 18]. The order of course topics was modified to present linked topics simultaneously so that each would reinforce the other [17]. Most course activities used student teams, and active and cooperative learning teaching methods were used extensively. At Louisiana Tech, participating faculty members met weekly to discuss the progress of students who were having difficulty [43]. Prior to teaching Connections students, faculty members at Colorado School of Mines attended a first-year course taught by another Connections faculty members. While this is an excellent way to develop an understanding of how other disciplines are taught, workloads made this difficult to accomplish [26].

IMPEC at NC State was taught by a multidisciplinary faculty team using a combination of cooperative, hands-on learning strategies and traditional lecturing formats [44]. All classes were team taught by professors from the mathematics, chemistry, physics, and engineering disciplines. Usually only one instructor at a time occupied the classroom, although all participating faculty members conducted workshops featuring integrated applications several times each semester.

The collaboration necessary to implement an integrated program can be cross-institutional as well. Prior to implementing IMPULSE, University of Massachusetts Dartmouth investigators formed a task force to learn about curriculum innovations taking place at other schools, most notably those that were members of the Foundation Coalition. Six faculty members visited Texas A&M for two days in October 1996 to study the integrated first-year program and subsequently invited a Texas A&M faculty member to conduct workshops and give presentations [107].

A survey of selected faculty members at Foundation Coalition institutions was conducted in 1997, with 112 respondents out of 384 surveys (29 percent). The survey was designed to assess differences between faculty members who had worked with the Coalition and those who had not [10]. The survey was repeated in 1998, and data from ASU faculty members are available for study [10]. The number of respondents is small (N = 35) since the sample reported is drawn only from ASU, but there are still clear and important messages in the results. A high percentage of both the FC faculty (85 percent) and non-FC faculty (90 percent) agreed with the statement "Faculty should help students integrate knowledge from two or more disciplines." This indicates that both groups surveyed value integration.

The perceptions of FC and non-FC faculty members differed most in the "Perception of Degree of Difficulty for Implementation of FC Strategies" section of the survey. Participants were asked to respond to several statements following the common root: "My perception is that the following aspects of the Foundation Coalition are particularly difficult to implement . . ." The results are shown in Table 1.

It is notable that the faculty members who are more likely to have tried to implement these strategies (the FC faculty) are more aware of the challenges of implementing them—this is indicated by the much larger fraction of FC faculty than non-FC faculty who indicated that the strategies would be difficult to implement. While the FC faculty members clearly indicate that curriculum integration is the most difficult of the FC strategies to implement, the non-FC faculty members do not share this perception. The authors would expect that perception to favor the expansion of curriculum integration—at least until non-FC faculty members discovered the difficulty of implementation. Non-FC faculty members, however, perceive coordination with other faculty members as the most difficult of these strategies. Since the implementation of an integrated curriculum requires a high degree of faculty collaboration, this perception becomes the greater barrier to implementation. This perception is also consistent with faculty perceptions of the faculty reward system—whereas teaching a course from the same notes still requires some preparation, teaching a compartmentalized course requires little or no

| **"My perception is that the following aspects of the Foundation Coalition are particularly difficult to implement:"** | **FC % (N)** | **Non-FC % (N)** |
|---|---|---|
| 1. The integration of topics/courses | 85% (11) | 38% (8) |
| 2. Use of technology to improve student learning | 31% (4) | 33% (7) |
| 3. Incorporation of cooperative learning | 62% (8) | 24% (5) |
| 4. In-class use of formal monitoring and assessment techniques | 69% (9) | 38% (8) |
| 5. Coordination with other faculty | 62% (8) | 52% (11) |
| 6. Overall workload | 85% (11) | 43% (9) |

*Table 1. Perceptions of FC and non-FC faculty.*

coordination with other faculty members. Since curriculum integration requires a considerable amount of faculty collaboration, there must be some motivation to overcome this imbalance.

### H. Integrative Learning Activities

Once the goals, objectives, and assessment processes for any curriculum are established, the next task is to design learning activities to promote student achievement of the objectives. An integrative learning activity that was nearly universal among integrated curricular initiatives was the inclusion of projects: design projects, research projects, and others. In addition to helping students make connections among subjects, projects sought to help students understand the applied and synthetic nature of engineering and the structure of the design process.

In $E^4$ at Drexel, laboratory projects totaling four hours per week were included in each of the first five terms, and students were required to participate in at least ten design project experiences versus none in the traditional curriculum [33]. The new programs that developed from Ohio State's Gateway program included hands-on laboratory experiences and team design/build projects [82], including a quarter-long design-and-build project that involves multiple fields of engineering. The ICE curriculum at Embry-Riddle featured required team projects involving group presentations evaluated by both the instructor and the students' peers. Cross-disciplinary team design projects were devised and supervised involving the collaboration of faculty members from engineering, mathematics, physics, and humanities [42]. Rose-Hulman's IFYCSEM included as many as six design projects per semester, although formative assessment reduced the number of projects to three [59]. Both semesters of the IMPULSE curriculum required an engineering design course. The first provided an introduction to graphics and involved substantial multidisciplinary design activity aimed at developing spatial reasoning skills. Projects in the first course emphasized Newtonian mechanics appropriate to freshman-level physics. For the second-semester design course the instructors used a mechatronics theme in keeping with the electromagnetic emphasis of the second-semester physics class [107].

### I. Building Academic and Social Connections

Although social connections may not have been a goal of integrated curricula (unlike learning community projects), the creation of a community of learners has been a notable result in their implementation [12, 26, 27, 71, 76–78, 102, 104]. Drexel's $E^4$ program seeks to build connections among disciplines by using a common schedule and integrated syllabus for all courses. In addition, presentations, homework assignments, tests, and exams are integrated, so class performance is itself some measure of knowledge integration. Drexel faculty used focus groups and review of student journals to more carefully assess these connections [38]. Researchers at the University of California at Berkeley coded interviews with seventy students to search for evidence of a variety of integration outcomes and found evidence of students developing connections among disciplines. McKenna and colleagues reported that approximately 70 percent of those interviewed found it helpful to learn real-world applications simultaneously with underlying engineering concepts [134].

Connections at Colorado School of Mines features a two-semester interdisciplinary seminar series in which students and faculty explore the interconnectedness of selected topics. While Connections sought to focus on the development of academic connections, researchers "quickly learned with the first pilot group that social and mentoring opportunities were more important to the students than the academic connections…" [26, 27]. In fact, the design of most integrated programs makes it nearly impossible to avoid the development of social connections—programs that have limited enrollment generally enroll students in the same set of classes. This technique, called clustering, places students in an environment where they can form cross-disciplinary study groups. Further, developing a faculty learning community that results from the collaboration necessary to design and implement an integrated program serves as a model for (and possibly a prerequisite to) developing student learning communities.

Recognizing that learning communities have been shown to promote a wide variety of desired outcomes, the designers of integrated programs have explicitly reinforced the relationship between curriculum integration and learning community development. Students in Arizona State's FIPE were registered for a total of fifteen hours (three for each of the courses included) and attended all classes as a unit. Training in team skills is explicit in the FIPE curriculum—eight of the nineteen contact hours during the first full week of the semester were devoted to structured activities designed to train students in team dynamics, and additional training modules were given each time new teams were assembled at the beginning of all major projects [17]. At Louisiana Tech the engineering component also included extensive training in team skills [43]. Texas A&M University creates clusters of students who attend the same sections of first-year math, science, and engineering courses. Each course cluster receives an enrollment of approximately 100 students, all of whom share the same schedule of courses. Although the enrollment is large, common scheduling and the use of the team format within individual courses create a community atmosphere [76]. At Drexel, groups of 100 students are assigned to a team of faculty that remains constant over the first five terms, and each student team elects a representative to attend weekly faculty meetings [30, 41].

The prevalence of cooperative learning in integrated programs supports the development of learning communities. All courses in IMPEC make extensive use of active, experiential, and cooperative learning, with the goal of addressing the full spectrum of student learning styles [44]. All laboratory experiments and most homework and in-class exercises are done by student teams. The collaborative activities have been designed to foster positive interdependence and individual accountability and to expose students to techniques in self- and team assessment [44].

## IV. Sophomore Integrated Programs

Although most of the integrated curricula developed and implemented thus far have focused on the first year of the engineering curriculum, some efforts have been made to integrate sophomore courses—the engineering sciences. One approach to constructing an integrated engineering science curriculum is referred to as the conservation and accounting framework, which rests on four ideas. The first is the concept of a system, "a region of space or quantity of matter set aside for analysis" [133]. The second is that extrinsic properties depend on the quantity of matter present. The third idea is that there are extrinsic properties (e.g., linear momentum, charge) that are conserved. The fourth idea is that changes in the amount of an extrinsic property within a well-defined system must be due either to transport across the boundaries of the system or

generation/consumption within the system. From these four ideas, the principles used in engineering science courses (e.g., thermodynamics, circuits, fluid mechanics, dynamics, statics) can be derived. More importantly, students can learn to apply these four ideas to construct mathematical models for diverse physical systems, even systems whose operation is explained by principles from multiple engineering science disciplines (e.g., motors, thermoelectric coolers).

Integrated engineering science curricula typically substitute several multidisciplinary engineering science courses for traditional engineering science courses. At Texas A&M University, four-course [114–123] and five-course [124] core engineering science curricula were developed to replace traditional sophomore engineering science courses [75]. Faculty members in electrical and computer engineering and mechanical engineering at Rose-Hulman Institute of Technology constructed a five-course sequence, referred to as the Sophomore Engineering Curriculum, over three quarters in the sophomore year to replace required core engineering science courses that were spread over the sophomore, junior, and senior years [127–133]. The new curricula at both institutions are still part of the required engineering curricula.

Assessment processes to identify changes in student learning at both institutions examined student performance on engineering science problems. At Texas A&M, faculty members developed an instrument that attempted to reflect questions students might see on the Fundamentals of Engineering (FE) examination. They gave the instrument to students who participated in the four-course core curriculum and a comparison group with similar population statistics of GPA and SAT scores. The core group performed better on this instrument than the comparison group. The mean score (out of 100) and standard deviations for the two populations were (Core = 56, 16) and (Comparison = 50, 13). A comparable gain on the actual FE would raise a student from the fiftieth percentile to about the sixtieth percentile. In addition, faculty members developed three achievement tests: statics, dynamics, and thermodynamics, and offered them to students who participated in the core curriculum in 1991–92. Faculty members offered one test at the end of the first sophomore semester and offered the other two at the end of the second sophomore semester. They results were compared to groups that had completed similar course material from the traditional curriculum. The exam coverage, mean, standard deviations, and population sizes for these exams are shown in Table 2.

Average performance of the core group was superior to that of the comparison group on the dynamics and thermodynamics examinations, but was inferior on the statics examinations. The thermodynamics comparisons are important because the comparison students were well into their junior years and had more engineering courses than the core students, yet the core students greatly outperformed the comparison group. However, it appears that the additional practice on statics problems by the comparison group resulted in superior performance in this engineering science.

At Rose-Hulman faculty members used a common final examination in the dynamics course to discern differences in student learning. Of the sixteen common multiple choice questions on the common examination given in the 1996–97 academic year, students in the Sophomore Engineering Curriculum (SEC) performed better on thirteen questions than students taking the traditional dynamics course. In the 1997–98 academic year, students in the SEC outscored students in dynamics on ten of the twenty common questions [131]. On problems in which student problem-solving methods were graded with partial credit, the differences were more dramatic. On the one common problem in 1996–97, 33 percent of the SEC students obtained an essentially correct answer, while 23 percent of the students in the dynamics course obtained an essentially correct answer. In 1997–98, faculty members constructed three common problems. The percentages of SEC students who obtained correct answers were (37 percent, 70 percent, and 46 percent), while the percentages for students in the traditional dynamics course were (17 percent, 22 percent, and 6 percent) [131]. The differences in student performance were one factor that mechanical engineering faculty considered in requiring the SEC for all mechanical engineering majors starting in the 1998–99 academic year.

## V. Summary Analysis

The analysis of integrated programs that have been offered to date has shown the following characteristics:

- The most significant long-term outcome of integrated programs may be faculty development. Significant collaboration among faculty is required to implement a successful integrated program and may lead to the development of faculty learning communities [15] through which faculty grow in their understanding of learning and teaching.
- Design projects have the potential to help students make connections among subjects, material, and applications. The process orientation of design holds promise for improving the systems thinking of engineering students.
- The implementation of integrated curricula has helped expand the use of cooperative learning and student teams, especially in design projects. The use of these pedagogical approaches and the clustering of students in multiple classes have aided the formation of learning communities. Learning

| Engineering Science Achievement Examination | Core Group | | | Comparison Group | | |
|---|---|---|---|---|---|---|
| | Aver. | Stand. Dev. | Pop. Size | Aver. | Stand. Dev. | Pop. Size |
| *Statics* | 65 | 6.0 | 78 | 78 | 7.0 | 173 |
| *Dynamics* | 51 | 8.0 | 78 | 35 | 8.0 | 93 |
| *Thermodynamics* | 66 | 7.0 | 78 | 57 | 7.0 | 165 |

*Table 2. Performance engineering science on achievement examinations.*

communities have likely played a role in improved retention and improved learning outcomes.

- Integrated programs have demonstrated various successful outcomes: improved retention (including improved retention for white women and underrepresented minorities), improved learning of disciplinary content, and (to a lesser extent) improved acquisition of nondisciplinary skills. Systematic analysis of improvements is hampered by the diversity of assessment methods and data used by different programs.
- The complexity of large-scale curricular change is notable, and faculty members discovered that a successful pilot program did not guarantee institutionalization. The process of curricular change is complex, and faculty members and administrators often changed their model of how institutional change occurs as they move from the challenge of initiating a pilot program to the challenge of scaling a program for a diverse student population in a college-wide curriculum to the challenge of sustaining an institutionalized curriculum [11].

Various institutions have piloted an integrated curriculum, obtained positive assessment data, and then either did not institutionalize the curriculum or institutionalized a curriculum for all students with significantly less integration than was characteristic of the pilot. This pattern suggests that numerous forces limit institutionalization.

First, integrated curricula that combine or connect material from two or more courses are newer concepts than curricula in which students complete degree requirements by taking a set of individual courses in which the only course constraints are prerequisite requirements. Since curricula composed of individual course requirements have existed for a long time, numerous administrative and institutional structures have developed to support such curricula. Integrated curricula, which overturn some of the assumptions underlying these structures, may require different administrative and institutional structures [11]. Constructing and maintaining alternative structures may require ways of thinking and investments of time and resources that an institution may be unwilling to adopt. For example, integrated curricula that connect material from two or more courses almost always require simultaneous enrollment in these courses. Such requirements reduce the flexibility available to students and administrators when assembling course schedules. Increased integration leads to reduced flexibility, while decreased integration offers more flexibility. Selecting a desirable operating point that balances the trade-off between integration and flexibility is a difficult decision. As a second example, integrated curricula that link courses from different departments, or even different colleges, may require administrative structures that facilitate coordination among participating departments. An institution may be unwilling or unable to conceive and/or provide such coordination structures. Senge and colleagues identified challenge of governance—changing administrative and institutional structures to support and sustain an innovation—as a process that tended to limit sustained implementation of innovations [165]. Studying change processes and organizational structures that limit the adoption of interdisciplinary curricular initiatives such as integrated curricula may present opportunities for future research.

Second, in complex curricular initiatives such as integrated curricula, multiple factors are changed simultaneously, confounding the cause of positive results. For example, retention data (including graduation rates) are the most common form of assessment used to study the relative performance of students in integrated programs and students in a comparison group. Yet retention is affected by many factors unrelated to integration: student volunteer effects, faculty volunteer effects, effects of a pilot program mindset on student, and others. Other assessment approaches such as nationally normed instruments or common local exams have shown increased performance for groups of students who participated in the integrated curricula. However, faculty members teaching integrated curricula often employed pedagogical approaches, such as cooperative learning, that are known to lead to superior learning outcomes [166, 167]. The assessment methodologies used make it difficult to determine how much the improved scores depend on integration or upon these pedagogical approaches. Confounded assessment data, unavoidable in the complex curricular changes implemented for integrated curricula, may tend to limit institutionalization and widespread adoption.

Third, despite stated intentions to help students make connections across topics and courses, none of the published assessment methodologies used for evaluation of integrated curricula have attempted to show that students are making improved connections. Although the importance of integration has been stressed in many articles, and institutions use the rationale of integration to help motivate offering a pilot and/or institutionalized version, no assessment processes and/or instruments have been developed to help define the degree to which a learner has integrated her/his knowledge. Opportunities for developing learning objectives and assessment methods related to integration are outlined in the next section.

## VI. Future Directions

Based on journal articles and conference publications, many faculty members are integrating material from different sources in their courses. From these efforts, the authors selected a subset that satisfied the criteria provided earlier in the article and referred to this subset as integrated curricula. The integrated curricula studied have similar motivations, structures, and positive outcomes from the pilot projects that were implemented. Even though integrated curricula have been developed and implemented at a diverse set of institutions, these attempts have generated more research questions than they have answered. In this final section of the paper, the authors offer several possible directions for future research.

### A. Assessment and Integrative Learning Outcomes

Several rationales supporting integration as a student outcome have been provided, yet no program has articulated learning outcomes and assessment processes associated with how well students are making connections. A critical step in developing integrated curricula is translating statements about the importance of integrative learning into outcomes and assessment processes. This will make it possible to acquire and analyze data related to success in achieving these outcomes. Categories for potential outcomes might include

- *Concept map-based outcomes*: A rubric could be constructed to evaluate student concept maps [152]. The rubric might include correct identification of critical concepts from each of the disciplines being considered, appropriateness of links between concepts, number of links between concepts, links that should have been made but were not drawn. Published descriptions of integrated programs do not mention the use of concept maps to evaluate the degree of integration achieved

by students in the program. Also, several researchers and companies are working on software tools to facilitate construction of concept maps. For example, Michigan State University is working on a National Science Foundation-supported project to provide tools to construct concept maps [168]. Commercial tools [169, 170] are also available. In addition to developing rubrics for evaluating concept maps, evaluating existing tools for developing concept maps and building more capable tools would be additional directions for future research related to integrated curricula.

- *Solving integrated problems:* Faculty members in some integrated curricula have formulated integrated exam problems and/or projects that require students to assemble concepts from two or more different disciplines to construct an appropriate solution. However, the desired outcomes and collection of program-level assessment data based on student performance on the integrated activities have not been published. Although many programs included activities that would encourage students to make connections or demonstrate to students connections among disciplines, published descriptions of integrated programs do not mention the use of integrated problems/projects to evaluate the degree of integration achieved by students in the program.
- *Design process evaluation:* Projects have played an important role in integrated curricula to date. Future research might attempt to clarify the degree to which inclusion of projects promotes each of the potential outcomes attributed to projects. Many design problems are naturally integrative activities. Established processes for the evaluation of design may be useful in assessing the ability of students to integrate knowledge from other courses or disciplines into their designs.
- *Transfer-associated outcomes:* The degree to which students were able to transfer their learning from first-year or engineering science courses to later courses was already mentioned as one of the factors motivating the development of integrated curricula. However, no results have been published that indicate the degree to which integrated curricula enhanced the ability of students to transfer their learning from courses in the integrated curriculum to subsequent courses. Developing methods to assess the transfer of mathematics, science, and fundamental engineering courses to later courses would be useful in evaluating integrated curricula.

Without well-defined outcomes, assessment claims for integrative learning remain unsubstantiated and, in many cases, confounded with the results of parallel interventions.

### B. Longitudinal Studies

The second future direction is related to the first, but suggests a very different approach. It may be that there are few short-term indicators of success in implementing an integrated curriculum. An integrated curriculum is not just a better way of graduating students with more of the same desired capabilities; rather, integration is about graduating a different kind of student—the kind that occurs by chance using our current educational approach—an "aberration" in the words of José Ortega y Gasset [142]. This kind of graduate might systematically result from an integrated curriculum. Under these conditions, the big payoff might happen after years have gone by—when employers see what these new students are capable of doing and figure out how to best use those abilities to advance their business, their industry, and the U.S. economy. Therefore, another possible future direction is a study that tracks the participants of an integrated program longitudinally after they graduate to see how their careers are different from students of traditional curricula. Both qualitative and quantitative approaches might be employed in the long-term longitudinal studies.

### C. Evaluating Alternative Integrated Curricular Approaches

Once processes to assess integrative learning have been developed, alternative integrated curricula might be implemented and analyzed. Integration can be achieved through a variety of structures and mechanisms, including loose coordination among instructors of concurrent courses, team-taught block-scheduled courses, full-scale learning communities of students who remain together in and (to a great extent) outside class. Curricula in which projects are specifically designed to serve as the principal vehicle to facilitate integration across courses might be constructed. Centerpiece projects at the Franklin W. Olin College of Engineering are examples of the type of project-based integrated curricula that might be envisioned. More closely linked courses in prerequisite networks might also improve integration. Alternatives in the scope of courses being integrated are also possible. Possible courses to be integrated include science, mathematics, engineering, communications (in a wide variety of forms), humanities, and social sciences. Integrated curricula have already included many different combinations of these courses and others are possible. Assessment processes should be designed to study relationships among structures, mechanisms, and scope of integration and both cognitive and affective outcomes.

### D. Meta-cognitive Outcomes

A few integrated programs explicitly articulated meta-cognitive outcomes—incorporating into the integrated program explicit instruction to the students about the reasons for integration and allowing the students to reflect on those reasons. In FIPE at Arizona State, each subject area—physics, calculus, chemistry, engineering, and English—gave weekly journal assignments. These required the students to reflect on their readings, re-examine concepts discussed in class, apply those concepts to other fields, and coherently explain and define the new ideas in language that a non-engineer could understand [17]. Another example is the Connections program at CSM, which underwent a significant shift of focus at the beginning of its second year. In response to feedback from students, faculty, and an outside evaluator, faculty members shifted the emphasis of Connections from *content* to *process*. The Drexel $E^4$ program assigned homework that required students to reflect on the design of the integrated program in which they were studying. Future research on how explicit awareness of and reflection on the integration of the curriculum creates improved integration and/or meta-cognition would be valuable in helping practitioners shape future designs of integrated curricula.

Curriculum integration is really a charge to do things entirely differently. If curriculum integration is desired on a broad scale, significant resources over a long time period will need to be invested in the assessment of learning outcomes related to integration, in the development and implementation of pilot programs, and in change processes that are likely to lead to sustained institutionalization and widespread adoption. Support should not be given for small-scale efforts with no support for growth—the commitment to financial support should only be made if the integrated curriculum

will become the primary curriculum used at an institution over the course of the project. Integrated curricula cannot survive as an "alternative" to traditional curricula because the cost of maintaining any curriculum dictates that only one primary curriculum receives the resources required to support it. One possible project might be to study the initiatives being supported by the Departmental Level Reform program and extract the degree to which these initiatives are promoting integration among departmental courses. This significant investment in integrated curricula might be made by funding agencies such as the National Science Foundation or by individual institutions, but will most likely be successful as a partnership of the two—external support with significant matching from the institution demonstrating its commitment.

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