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The Center for the Advancement of Engineering Education: A Review of Results and Resources*

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The Center for the Advancement of Engineering Education (CAEE) conducted research on the learning experiences of engineering undergraduates, the teaching practices of engineering faculty, and methods to build capacity to teach engineering and conduct high-quality engineering education research. This paper has two goals: to present a sample of key findings from these multiple research threads and to highlight the various tools and processes developed by the CAEE research team that are available for use by others. These resources include survey, interview, and design task instruments, as well as a year-by-year guide to the development and implementation of the Academic Pathways Study (APS), CAEE's in-depth study of engineering undergraduates. A more extended discussion of findings is available in CAEE's final report, *Enabling Engineering Student Success*. The final report and the tools for researchers can all be viewed and downloaded through the CAEE website at http://www.engr.uw.edu/caee/. CAEE was funded by the National Science Foundation from 2003 to 2009.

Keywords: engineering education; engineering undergraduate learning; engineering teaching; research instruments; early-career professionals; engineering practice; educator decision making; engineering education research community

1. Introduction

Engineering students are entering a world characterized by *grand challenges* [1]. To help the engineering education community prepare students to meet these challenges, the Center for the Advancement of Engineering Education (CAEE) engaged in research that (1) focused on the student experience and provided significant insight into the learning of engineering across diverse undergraduate populations and environments through longitudinal, cross-sectional, and targeted studies; (2) created a portfolio program to assist engineering graduate students in preparing for teaching; (3) focused on faculty by providing insights into how engineering educators make teaching decisions as they engage with students; and (4) fostered a diverse cadre of leaders and change agents in engineering education who can conduct high-impact research.

The CAEE findings that shed light on the aspects of engineering education listed above can be described by the expression "a thousand people, a thousand stories." This expression applies equally to students, faculty, and engineering education researchers. In essence, our research findings provide a deeper understanding of some of the factors that lead to the rich and variable experiences of each of these populations. Our research on engineering student pathways has shown us that, while students in our study who stay in engineering are similar by many measures to those who leave, some students remain uncertain about what it means to be an engineer, even in their fourth year. The graduating seniors who participated in our study were less satisfied with their faculty and teaching assistants than were those entering as first-year students, even though the seniors interacted with faculty and teaching assistants more frequently. In our research on engineering faculty and how they make teaching decisions, we found that faculty in our study purposefully engaged in teaching practices that they felt increased students' motivation to learn. Finally, CAEE's work in helping to develop the engineering education research community demonstrated the important role that membership in a community of practice played in helping individual researchers develop their expertise and identities as engineering education researchers.

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In this paper, we first present a brief overview of the seven years of research conducted by CAEE. An overview of the center is presented in the next section. Sections 3 through 6 discuss each of CAEE's main research threads and present a sampling of research results. The last two sections describe the key research and program resources that CAEE has made available to the community, concluding with thoughts about future research directions for the field of engineering education.

2. Center overview

The Center for the Advancement of Engineering Education was a large, multi-institutional research center that focused on several aspects of educating today's engineering students. Two National Science Foundation directorates funded CAEE from 2003 to 2009: Engineering, and Education & Human Resources. CAEE began as a group of researchers from five universities: Colorado School of Mines, Howard University, Stanford University, the University of Minnesota, and the University of Washington (the lead institution). Over the course of the grant, colleagues from ten other universities across the U.S. joined this core team. Cumulatively, CAEE directly involved 63 faculty and staff, 41 graduate students, and over 40 undergraduate students directly in the research. In addition, 49 Institute Scholars undertook year-long research projects as part of CAEE's Institute for Scholarship on Engineering Education. Many of these participants were new to engineering education research and, encouragingly, have continued their careers in the field. Representatives from several national organizations, including the Women in Engineering Program Advocates Network (WEPAN), the National Action Council for Minorities in Engineering (NACME), and the Center for the Advancement of Scholarship on Engineering Education (CASEE), also supported CAEE's research.

CAEE's research targeted four broad areas:

1. Understanding the engineering undergraduate learning experience and school-to-work transition (Academic Pathways Study, APS)
2. Investigating engineering teaching through the analysis of engineering educators' teaching-related decisions (Studies of Engineering Educator Decisions, SEED)
3. Developing and implementing a teaching portfolio program and materials targeted at supporting engineering graduate students interested in teaching careers (Engineering Teaching Portfolio Program, ETPP)
4. Expanding the engineering education research community by engaging researchers (many of whom were new to engineering education research) in year-long Institutes and developing models as the basis for future community building activities (Institute for Scholarship on Engineering Education, ISEE).

A complete list of publications and presentations made by the CAEE team, as well as an array of resources that are available for use by others, is included in the CAEE final report, *Enabling Engineering Student Success* [2], and on the CAEE website at http://www.engr.uw.edu/caee [3]. These resources include survey, interview, and design task instruments, as well as program materials and research guides.

3. Academic pathways study

The Academic Pathways Study (APS) examined different populations of students and recent graduates with a goal of describing the learning experiences of today's engineering undergraduates. APS relied on both quantitative and qualitative research methods. Methods and data sources included surveys, structured interviews, semi-structured (ethnographic) interviews and observations, engineering design tasks, focus groups, and academic transcripts. More than 5500 students, faculty, and early-career engineers participated in APS research.

The APS research questions focused on four aspects of becoming an engineer:

1. *Skills*: How do students' engineering skills and knowledge develop and/or change over time?
2. *Identity*: How does one's identity as an engineer evolve? More specifically, how does student appreciation, confidence, and commitment for engineering change during the undergraduate educational experience? How do these changes impact student decisions about pursuing engineering after graduation?
3. *Education*: What elements of students' engineering educations contribute to changes observed in their skills and identity? What do students find difficult, and how do they deal with the difficulties they face?
4. *Workplace*: What skills do early-career engineers need as they enter the workplace? Where did they obtain these skills?

These research questions were examined in six separately led studies of varying size and duration. The studies' participants and data collection methods are described briefly below.

3.1 APS study samples and methods

- *The Longitudinal Cohort* research explored the learning experiences of 160 engineering undergraduates on four campuses over four years. Data collection methods included the Persistence in Engineering (PIE) survey, structured and semi-structured interviews, and engineering design tasks.

- *The Broader Core Sample* was a cross-sectional study of over 800 engineering undergraduates at the four Longitudinal Cohort campuses that used a shorter version of the PIE survey. A primary goal of the Broader Core Sample was to serve as a pilot for the survey used with the Broader National Sample.
- *The Broader National Sample* (also referred to as "APPLES" or the "APPLE Survey") was a cross-sectional study of over 4200 engineering undergraduates at 21 campuses across the United States. Participants took the online Academic Pathways of People Learning Engineering Survey (APPLES), developed from the PIE survey through the pilot described above. Campuses were chosen for participation to ensure a broad range of size, mission, demographic makeup, and geographic location. Results specific to the Broader National Sample are presented in more detail in the technical report "Exploring the engineering student experience: Findings from the Academic Pathways of People Learning Engineering Survey (APPLES)" [4].

Three smaller-scale studies complemented the longitudinal and national studies above:

- *The Transition to the Workplace Studies* included a series of cross-sectional interviews and observations that generated six independent data sets involving a total of 101 early-career engineers and 15 of their managers. Participants were employed by private companies and public agencies.
- *The Difficult Concepts Study* focused on two specific concepts (force and voltage) that are often hard for engineering students to master. Nineteen engineering seniors (on one CAEE campus) participated in hour-long interviews that probed their knowledge of concepts relevant to their major. The interview questions were developed using a Delphi process that involved 23 faculty members on several campuses.
- *The Single-School Cross-Sectional Sample* was a two-phased study of undergraduate engineering students on a single campus. A fall-semester survey targeted 40 students in each of the freshman through senior classes (160 total participants). A second survey administration in the spring added transfer students and was supplemented by several small focus groups.

For more information on the design and methodologies of the Academic Pathways Study, see the CAEE technical report *An overview of the Academic Pathways Study: Research processes and procedures* [5].

3.2 Selected APS findings

Selected findings from various aspects of the Academic Pathways Study are grouped into three major categories: Choosing and Sticking with Engineering, Learning Engineering Skills, and Thinking About the Future and Joining the Engineering Work Force.

3.2.1 Choosing and sticking with engineering

One perhaps unexpected finding of the study is that persistence in engineering majors is comparable to that in other majors; i.e., students who start with an engineering major are as likely to continue with their major as are students in other fields. However, there were findings that should concern engineering educators. For example, those who persist in engineering—even students who seem to be deeply committed—can have significant doubts about staying in their engineering majors.

The study indicated that those who leave engineering majors are disproportionately from groups underrepresented in engineering, including first-generation college attendees. This disproportionate movement out of engineering results in a less diverse graduating cohort. In addition, fewer students migrate *into* engineering majors after starting college, which results in a net loss of students of over 15%, which is more than most other majors. This low in-migration is partly related to the rigid curricular requirements and heavy course loads of some engineering programs. Students who do not begin college as engineering majors often need to take numerous prerequisites to get into an engineering program, which can necessitate extending their undergraduate studies by one or more terms. Although in-migration is low, it is worth noting that the small fraction of engineering graduates who migrate from another major includes many students from underrepresented groups.

The APS results indicated that there are multiple pathways into engineering and that facilitating access to non-traditional pathways has the potential for broadening participation in engineering. Even those students who seem firmly committed to majoring in engineering may have doubts about it being the right pathway for them. To address this potential for doubts, students should be encouraged, through early-college experiences, to explore and choose pathways tied to important motivational factors that enable students to "try out engineering." The study also emphasized that students can and do learn about engineering through multiple sources—not only from coursework but also relationships with faculty, advisors, and peers; co-op/internship experiences; and extra-curricular activities [6–18]. (More on these findings can be found in Section 2.2 of the CAEE final report [2].)

Focusing specifically on influences on entry into engineering, the study also found that students are motivated to study engineering by a wide variety of factors. These factors include psychological reasons, wanting to contribute to social good, desire for financial security and, in some cases, the feeling that an engineering degree could serve as a steppingstone to another profession. Intrinsic psychological and behavioral motivation are strong among all engineering students. However, some of these factors have more influence with certain demographic groups. For example, motivation by mentors is stronger among women, whereas men are motivated more strongly by the "making" and "doing" aspects of engineering (behavioral motivation). Motivation is related to several important outcomes. For first-year students, the enjoyment of engineering for its own sake (psychological motivation) is correlated with the intention to complete an engineering major, and, for seniors, it predicts the intention of entering the engineering work force or graduate school [4, 6, 7, 9–11, 14, 16, 17, 19–23]. (More on APS findings on motivation can be found in Section 2.3 of the CAEE final report [2].)

Just as motivation to study engineering is not the same for all students, neither are the ways that students construct and experience their college education, e.g., their level of engagement with their courses and teachers, and how they combine and balance coursework and extra-curricular involvement, including co-op, internship, and research opportunities. Some students engage strongly in everything they do, others are more measured and focused in their involvement, and some are largely uninvolved in out-of-classroom activities.

The study indicated that women tend to be more involved in both engineering and non-engineering extra-curricular activities throughout their college careers and that they ascribe more importance to these activities than do men. These trends also vary with individual levels of psychological motivation and confidence in professional and interpersonal skills, and also by class standing (i.e., first vs. senior year). Equally important, the "lived" experiences of students vary, e.g., in terms of a feeling of curricular overload or of pressure to represent one's demographic group [6, 7, 14, 18, 21, 24–30]. (More on APS findings on the college experience can be found in Section 2.4 of the CAEE final report [2].)

3.2.2 *Learning engineering skills*

Engineering students in our study reported experiencing considerable intellectual growth during their undergraduate years, learning to apply fundamental math and science tools, and learning to take on substantial challenges in their design work. Furthermore, their college studies also bolstered their confidence in many of the professional and practical skills that are increasingly important in engineering practice.

However, the demands of studying engineering may result in students being unable to take advantage of other parts of a college education. For example, the APS engineering students reported lower gains in personal growth and fewer opportunities to study abroad than students in other majors did. Consistent with the demands of engineering coursework, some engineering students reported a sense of curricular overload.

Compared with first-year students, seniors were less involved in their engineering courses, less satisfied with their instructors (although they typically interacted with them more frequently), and less satisfied overall with their college experiences. In spite of these relative differences, seniors reported having significant learning experiences, especially those that offered an in-depth experience and presented them with a challenge.

Students learn about engineering and develop an engineering identity from a variety of sources. These include co-op and internship experiences, their college coursework, engineering faculty and instructors, extra-curricular activities, and personal contacts. Results of the study indicated that the sources students cite do not vary much by gender or underrepresented minority status.

By their senior year, most students in the Longitudinal Cohort saw problem solving, communications, teamwork, and engineering analysis as key engineering competencies. They also thought of design in terms of more engineering-specific language than they did as first-years. However, in approaching design problem solving, most Longitudinal Cohort students did not appear to consider problem context (e.g., social, environmental, and economic context) more in their junior and senior years than they did in their first and sophomore years. Women considered certain aspects of context more than men did, but this did not change significantly over the course of undergraduate study.

In addition, engineering seniors did not perceive the broader range of professional and interpersonal skills as being any more important than did first-year students, even though the seniors had engaged in project-based learning, design experiences, and, for some, co-op or internship experiences. These important professional and interpersonal skills include leadership, public speaking, business abilities, as well as communications, teamwork, and social skills [6, 9, 10, 14, 17, 18, 30–41]. (More on

APS findings on students learning engineering skills and their perceptions of engineering can be found in Sections 2.5 and 2.6 of the CAEE final report [2].)

3.2.3 Thinking about the future and joining the engineering work force

About 30 percent of the engineering students in the APS had post-graduation plans that focused exclusively on engineering (work and/or graduate school). As a group, these students were strongly motivated to study engineering for intrinsic psychological reasons and were likely to have had co-op and/or internship experiences. In general, these same students were less confident in their professional and interpersonal skills than those who were considering non-engineering professional endeavors after graduation.

Most of the other students (roughly 70%) visualized their careers as combining both engineering and non-engineering components. Some of these students expected different degrees of engineering content in their work, which would change as their careers progressed. Others may still have been uncertain, even close to graduation, as to whether an engineering or non-engineering path would be the best fit for them. These patterns might also have been influenced by the specific focus of the institution that students attended [4, 7, 10, 42–47]. (More on APS findings on students' career plans can be found in Section 2.7 of the CAEE final report [2].)

Those students who chose to enter the world of work after graduation faced a range of challenges. For one, they often found that the problems that they ended up working on were more complex, ambiguous, and/or poorly defined than the problems that they solved in school. The structures of their new work environments were also often unfamiliar and multi-faceted, and it was sometimes difficult for newly hired engineers to find the information they needed. A number of interviewees felt that they were not sufficiently apprised of the "big picture", i.e., they were not given an accurate idea of where they and their work activities fitted into the goals of the work group or company.

These new hires also found that they were working with larger, more diverse teams than in their undergraduate years—teams that were made up of people with widely varying technical skills and roles on the project, including engineers and non-engineers, program managers, and other coworkers, as well as customers or clients. These recent graduates often had to learn new terminology and new communication skills. Graduates reported feeling underprepared to address engineering problems and decision making in real-world engineering practice, where, in addition to the complexities of multidisciplinary teams, decisions were often based on both technical and non-technical factors [43–46, 48]. (These and other APS engineering workplace findings are presented in Section 2.8 of the CAEE final report [2].)

3.2.4 Student perspectives on significant learning opportunities

Our research also allowed us to capture student perspectives about their learning experiences. Based on interviews with a sample of graduating seniors from one of the campuses in the Longitudinal Cohort, a significant learning opportunity was viewed as having at least some of the following qualities [49]:

- Connects with what students find meaningful (applicable, experiential, real-world, hands-on)

  "I like the senior electives because it's less about just doing the problems for my own sake so that I can learn the material, but because it's applicable outside of what we're doing in class. Often the projects are a lot more real-world, so to speak, than other classes that I've taken."

- Presents students with a challenge, conflict, dilemma, frustration, and/or obstacles

  "And then another thing was his homeworks were really hard, so I learned a lot from them. They were painful, but by the end of it I felt like—I felt a lot more confident about my mathematics ability and physics and all of that, just because I've gone through this kind of gauntlet of really horrible homeworks."

- Asks students to be self-directed learners

  "Because we were left to our own devices a lot. We had an advisor, of course, and we met weekly and got a lot of feedback, but she—you know, despite the fact that we would have liked a little more direction, I think that in the end, it was good for us to have that experience of trying to make it on our own and make the decisions by ourselves."

- Gives students ownership of the experience

  "I was also just given responsibility, too. There wasn't someone saying, you know, this is due in a week or write a paper about, you know, this, or do these homework assignments. It was, you know, if this is something you feel strongly about, you should do it. If not, we should find something else."

- Facilitates a broader vision, shows how the pieces fit together

  "I think working on SAE [Society for Automotive Engineers] and with various team projects has been probably the biggest learning experience, just because . . . if you're trying to get a system to work, you can't build all the parts, you have to call people . . . ask them about their product and try to make things, I guess, fit together.

3.2.5 Using APS findings to affect conversations and change

Following on from the observations made by the students that are reported in the previous section, one significant question for the engineering education community is, *How do we ensure that more students encounter educational experiences that incorporate these important qualities?* Thinking in terms of the APS research, a more specific question is, *How can the APS results be used to affect practice?*

We offer several suggestions on how to use the APS results based on our work. First, the CAEE team developed a set of data-driven workshops that present the APS findings in a workshop design informed by the SEED research (described in the next section) to help attendees bring research findings to practice [50]. Second, the CAEE team developed a set of questions that are informed by the APS research findings that are intended to facilitate discussion on how a particular topic motivated by research findings could play out in a classroom or campus. These questions, called Local Inquiry Questions, are described in Section 2.10 and are also reproduced in list format in Appendix D of the CAEE final report [2]. Third, the APS team has made available the APPLE Survey questions and interview protocols for use by others. The team has already seen a number of uses and adaptations of these materials by other researchers.

Additional, less formal ways of responding to these findings are possible: an individual engineering educator considering how APS findings might affect how a particular topic is taught, or a conversation between an engineering educator and a faculty development professional about effective teaching. It might also take the form of discussion at the department or institution level between administrators, staff, and faculty as part of a broader conversation on how effectively a particular program is in enabling academic and professional success for students on a variety of educational pathways.

4. Studies of Engineering Educator Decisions (SEED)

The Studies of Engineering Educator Decisions component of CAEE investigated engineering educators' approaches to teaching using the lens of their teaching decisions. The primary SEED research questions were as follows:

- How do engineering educators commit to action in teaching?
- To what extent and in what ways do engineering educators enact effective teaching practices?
- What are the strengths and limitations in how engineering educators conceptualize students?
- How can a focus on decisions and decision narratives be used in faculty development?

4.1 SEED methods and study sample

In semi-structured interviews, faculty at a large, public, research-oriented university were asked to describe two recent teaching decisions: (1) one made during the planning stage for a class and (2) a second that was made in "real time" during interaction with students. The team developed the interview protocol based on the Critical Decision Method (CDM) approach. The four-page protocol is available on the CAEE website's Resources section.

The 31 SEED participants represented nine of ten engineering departments at the university. There were twelve full and seven associate professors with tenure, seven assistant professors on tenure track, and five non-tenure-track faculty. Four of the participants also had higher-level administrative roles within the university. Women were intentionally oversampled, resulting in 23 male and 10 female faculty participants.

Summary of SEED Results and Observations

The results of the SEED research provided insight into several aspects of individual teaching practices:

- Most of the educators who were interviewed reacted positively to the emphasis on decisions and decision making, and all were able to provide rationale for their decisions. Considerations of time and allusions to prior decisions were both common features of their rationales. The study participants also collectively mentioned a variety of sources of information as being useful in decision making, although results from education research were mentioned infrequently as a source.
- There were five distinct patterns in terms of the educators' satisfaction with personal teaching decisions. These patterns included (1) participants mentioning that they were not optimally satisfied with their decisions, but they considered the outcome to be good enough; (2) not being satisfied but also not having sufficient control to change the situation; (3) not being satisfied but simply having to focus on something else; (4) being satisfied but at personal expense; and (5) being satisfied, with no reason for additional change.
- In addition to focusing on decision processes, the team analyzed the interviews to explore educa-

tors' use of teaching practices considered effective at helping students develop intrinsic motivation to learn. Study participants reported using practices such as helping students see the relevance of material, making sure students feel connected to the learning group, and trying to ensure that students experience productive levels of engagement and challenge. There was less frequent mention of providing students with opportunities for autonomy, assuring that all students felt respected, and providing students with opportunities to demonstrate their growing competence.

- With a goal to understand the broader issue of how engineering educators conceptualize engineering students, the team examined the narratives to learn more about how engineering educators differentiate among students. All of the educators made distinctions among students at some point, and student behaviors were the most prevalent basis for this differentiation. Differentiation based on other dimensions (including what students know, their educational classifications, their demographic classifications) was also prevalent but less so.
- The outcomes of this research may assist faculty development personnel in better understanding their faculty clients. Additionally, faculty developers might use decision narratives to initiate fruitful discussions with faculty on problematic teaching issues and other concerns. One exciting feature of using decision narratives in research is the idea that the process of doing the research is potentially significant for all parties involved, including the researchers.

5. Engineering Teaching Portfolio Program (ETPP)

The Engineering Teaching Portfolio Program was designed for engineering graduate students and others (including postdoctoral researchers) who are interested in pursuing a faculty career by helping to expand their thinking about and understanding of teaching through the development of teaching portfolios. The program design goals were as follows:

- Assist future engineering faculty in developing a teaching portfolio
- Encourage ETPP participants to reflect on teaching in general and their approaches in particular
- Investigate the impact of the program on session participants and understand the processes that were important in achieving that impact.

Small groups of graduate students met weekly in an eight-week program to work on preparing a teaching portfolio consisting of a teaching philosophy statement, two to five annotated teaching artifacts, and a diversity statement.

ETPP was distinctive in that it combined social interaction with a peer-facilitated structure. ETPP also included opportunities for students to learn about teaching by producing something valuable to them as a future faculty member (i.e., the portfolio), supported conversations about diversity prominently, and involved discussions about teaching in a way that would enhance and support participation by people with a wide range of prior experiences.

There were approximately 100 program "graduates" over 11 offerings held between spring 2003 and summer 2006. There were also several smaller-scale spinoff efforts. An examination of the multiple offerings of ETPP suggests that the educational power of developing a portfolio can come from consideration of the significant questions that are often associated with portfolio construction. Example questions include, who am I talking to, what exactly do I want to say about my teaching, who judges teaching, how do I provide evidence of my strengths as a teacher, and what counts as "good" teaching?

6. Institute for Scholarship on Engineering Education (ISEE)

Three cycles of the Institute for Scholarship on Engineering Education involved a diverse group of 49 Institute Scholars in engineering education-related research projects. The participants represented 20 institutions and included faculty, graduate students, and staff. In addition to expanding the community of engineering education researchers, an additional goal of ISEE was to develop models that could be used to support similar efforts by other engineering education researchers in the future. The research objectives were as follows:

- Expand the engineering education research community on the CAEE campuses and nationally
- Formulate principles and develop models for building and sustaining the engineering education research community
- Investigate the pathways of scholars into the field of engineering education research.

6.1 Three cycles of the Institute for Scholarship on Engineering Education

The three Institute cycles were one year long and were each designed with a different theme. The 2004–2005 Institute (hosted by the University of Washington) focused primarily on classroom changes under the broad theme of "classroom as lab." For the 2005–2006 Institute (hosted by Stanford University), projects sought to impact engineering education on each participant's campus (i.e., a theme of "campus as lab"). The 2006–2007 Institute (hosted by Howard University) focused on "nation as lab" with the theme, "Advancing Engineering Education Research to Meet the Needs of the 21st Century."

Each year-long ISEE cycle consisted of five main phases:

1. Design and/or adaptation of the Institute model for the current cycle
2. Recruiting Scholars for the current year
3. A week-long launch event ("Summer Summit") at the host school
4. Implementation of various activities during the academic year to support Scholars in their studies
5. A concluding Leadership Summit event that brought Scholars together to share the results of their research projects with each other and a national audience.

The Summer Summit engaged the Scholars in the processes of engineering education research and introduced many to new techniques and ideas in the field of education research. Activities and discussions during the week helped Scholars refine their research questions, decide on appropriate methodology, and begin forming a community with their fellow Scholars and the ISEE team.

Scholars for the first two Institutes were recruited primarily from the CAEE campuses. The Scholars for the final 2006–2007 Institute were recruited through a competitive, national application process and were asked to address aspects of diversity in their projects. Posters summarizing Scholars' work were presented at Leadership Summits held as part of special sessions at the national FIE Conferences in 2005 and 2007 [51, 52].

6.2 Institute outcomes

The three Institutes helped a total of 49 faculty members, graduate students, and staff, representing 20 institutions, to develop their skills as engineering education researchers. Each Institute Scholar was assisted by members of the ISEE team and their peers in the process of designing and carrying out an engineering education research project. Many have continued to incorporate this aspect of education research in their academic careers.

The Institutes also helped to identify and develop strategies that have proved useful in helping Scholars face common challenges in undertaking engineering education research. These strategies include techniques for navigating the human subject's research approval process and how to facilitate integrating with the engineering education community.

6.3 Developing models for research community building

As part of staging the three Institutes, the ISEE team worked to formulate principles and develop models for expanding and supporting the community of engineering education researchers. The three Institutes also served as specific examples for others interested in organizing similar community building activities.

The ISEE model describes the content and activities used to prepare new engineering education researchers, with an emphasis on building community within each cohort of Scholars, as well as the larger engineering education community. This model includes a set of specific design principles, including those that highlight techniques for recruiting prospective Scholars and the importance of interactive, community-centered activities.

6.4 Investigating pathways into engineering education research

The ISEE team also investigated the pathways that researchers followed into the field of engineering education research. Results from a study of 13 engineering education researchers described two significant aspects of their pathways into the field of engineering education research: the importance of a community-of-practice perspective and the development of a composite identity. This study of pathways further extended the team's understanding of capacity building for engineering education research that was developed during the implementation of the three Institutes.

7. CAEE resources for use by others

Sections 3–6 of the final report presented a high-level summary of the main threads of CAEE's research, with a sampling of the significant results. These results have been presented in more than 130 papers and are described in more depth in CAEE's final report [2]. Another important outcome of CAEE's research, in addition to the formal results, was the creation of a wide range of materials that can be used by research colleagues and others interested in advancing engineering education on their campuses or on the broader national stage. The CAEE team has seen a number of these resources getting significant use, either through specific inquiries or downloads from the CAEE website. All of these materials are available on the CAEE website, http://www.engr.uw.edu/caee. A brief description of some of the key resources follows.

7.1 CAEE final report

Enabling Engineering Student Success, CAEE's final report [2], presents a summary of findings drawn from the multiple research threads, thoughts from the research team on implications, impact examples, and an extensive list of CAEE publications, presentations, and workshops.

7.2 Research instruments and guides

7.2.1 The Academic Pathways Study: Detailed study description and instruments

Two documents describe significant aspects of APS research. The first is a guide to the design and implementation of the study and the second is a technical report that presents detailed results from the APPLES national survey, administered in 2008.

The technical report *An overview of the Academic Pathways Study: Research processes and procedures* [5] provides a year-by-year description of the Academic Pathways Study, from initial design to implementation. In many cases, the report discusses the trade-offs and reasoning behind research decisions. Of particular interest are the specific instruments and protocols for the different research methods and sample cohorts. The following instruments are included as appendices in the technical report:

- Structured interview protocols
- Engineering design task protocols
- Ethnographic (semi-structured) interview protocols
- Workplace interview guides
- Persistence in Engineering (PIE) survey instrument
- APPLES (survey) instrument.

The second document, the technical report, *Exploring the Engineering Student Experience: Findings from the Academic Pathways of People Learning Engineering Survey (APPLES) (CAEE-TR-10-01)* [4] presents findings from CAEE's national APPLE Survey of over 4200 students on 21 campuses, conducted in 2008. Both of the above technical reports are available on the CAEE website.

7.2.2 Studies of Engineering Educator Decisions: Interview protocols

The Studies of Engineering Educator Decisions (SEED) used a semi-structured interview approach to investigate these two types of engineering faculty teaching decisions. The interview protocol is available from the Resources section of the CAEE website.

7.3 Program materials

Two components of CAEE's activity focused on creating and implementing programs that had similar goals of building community. One activity targeted engineering graduate students interested in teaching careers (Engineering Teaching Portfolio Program, ETPP) and the other engaged engineering faculty and graduate students interested in developing education research skills (Institute for Scholarship on Engineering Education, ISEE). Both programs were successfully implemented in different offerings over several years, and each program provided a powerful means of reaching other audiences. Each program has also been adopted and/or modified for use by others. The available program materials are summarized below.

7.3.1 Engineering Teaching Portfolio Program

The Engineering Teaching Portfolio Program (ETPP) focused on enhancing the understanding and skills of engineering graduate students interested in teaching careers. The ETPP team developed a detailed curriculum and supplemental materials for the program.

The ETPP curriculum and session worksheets provide detailed step-by-step guidance for each session, including objectives, handouts, and suggested assignments. Supplemental materials used in the original offerings (2004–2005) provide examples and background information. The curriculum and supplemental materials are available from the Resources section of the CAEE website.

7.3.2 Institute for Scholarship on Engineering Education

The Institute for Scholarship on Engineering Education (ISEE) was focused on growing the community of engineering education researchers. A description of the Institute model (with a focus on establishing a community of practice) is described in a 2006 ASEE paper that also provides information for those interested in staging similar capacity building events [53]. A CAEE research brief provides highlights of the paper and is linked on the Resources page of the CAEE website.

The team has also made available a representative Institute Summer Summit Schedule that describes the launch event for each Institute. The schedule provides an example of the organization and suggested topics covered during the five-day meeting that began each year-long Institute cycle. The sample schedule is available from the Resources section of the CAEE website.

7.4 Research briefs

As a way to provide a quick introduction to CAEE's research for multiple audiences, the team created a series of research briefs that summarize findings and implications from published papers in short, easy-to-scan documents. Over 60 articles and papers are summarized in the briefs, which are published on the CAEE website. The research briefs are accessible through the CAEE website under the following five subject themes: (1) Understanding Student Pathways and Experiences, (2) Examining Student Learning and Skill Development, (3) Exploring Issues of Diversity, (4) Developing Community and Building Models for Engineering Education Research, (5) Developing Effective Teaching Practices.

7.5 Local inquiry questions

CAEE developed a set of Local Inquiry Questions (LIQs) that can be used to guide thinking and research on specific campuses and in individual classrooms. These LIQs are based on the results of CAEE research and are designed to facilitate reflection on a range of key topics—everything from entry into engineering majors to transitions into the workplace. See Section 2.10 and Appendix D of the CAEE final report [2].

7.6 Ideas for future research

The final report concludes with a diverse array of research questions inspired by and extending CAEE research. Individual centers and programs are no doubt already pursuing some of these ideas, but others might guide future work, especially for graduate students and other new engineering education researchers. See Section 7.2 and Appendix E of the CAEE final report [2], as well as the following section of this paper.

8. Future directions

Over the seven years of funding, CAEE conducted research on several facets of the engineering education system. On the learning side of the teaching–learning equation, we conducted an in-depth study to understand the engineering student experience from *the student perspective*. On the teaching side of the teaching-learning equation, we conducted an innovative study of *engineering educator decision*

Table 1. Ideas for future research (selected from the complete set of questions in Appendix E of the CAEE final report [2])

On Pathways
- What characterizes informed decision making with respect to a student's choice to major in engineering? What factors are considered? What trade-offs are made? How do these factors and trade-offs differ for students with different backgrounds? Do they differ for students at various points in their pathways to an undergraduate degree?
- What are the lessons learned from students' transitions to the workplace and graduate school? How do these lessons vary with industry, graduate school, size of organization, etc.? How can these lessons be fed back into and inform undergraduate education? How can they be fed forward to graduate schools and engineering firms to help students to make a smoother transition?

On Learning Engineering
- What engineering concepts are most difficult for students to learn and why? What makes some concepts more difficult to learn than others? How can we better teach difficult concepts?
- How can students be taught to consider context better in engineering design? How can students be taught to take into account users and other important stakeholders in engineering design better?
- In what ways can reflecting on educational experiences enhance students' intellectual and professional growth? How can we help students learn and practice this kind of metacognitive reflection?

On Significant Learning Experiences
- How can we help students link what they are learning in extra-curricular activities to what they learn in the classroom?
- How can we better support students' participation in international learning experiences? What do students who engage in these experiences learn?

On Engineering Knowledge
- What mathematics knowledge and skills are needed at what points throughout the engineering curriculum?
- What are the fundamental concepts that are common to multiple engineering disciplines? What is the "minimum set" of skills and concepts necessary for engineering practice? How do the increasing complexity and scale of engineering problems affect what we consider to be the "base" of engineering knowledge?

On Teaching Engineering Students
- What aspects of an engineer's education are best served by campus-based experiences? By industry-based experiences? By technology-enhanced experiences? By service-learning experiences?
- In what ways can a structured examination of decision making guide faculty with their teaching?
- What apprenticeship models of teaching can be employed to teach key elements of engineering practice?

On Researching Issues in Engineering Education
- In what ways do the process and experience of conducting research on learning and teaching change how an educator designs learning experiences?
- How can we support engineering faculty who want to pursue engineering education research?

On Bringing About Change in Engineering Education
- How can the extensive variability of engineering students and their pathways through their education be leveraged in service of improving engineering education?
- How do we support faculty and program planners in effective change?
- What technological infrastructure (e.g., databases, tools) would accelerate both research advances and the rate at which research results are used to influence educational practice and outcomes?

making and developed a way to give graduate students insights about the teaching experience (with minimal institutional resources).

While our insights on student and educator experiences are compelling, they are essentially only a snapshot in time. To achieve a critically important continuation of the work, the community is in need of more scholars to advance understanding of both the student and faculty stories over time. To contribute to this effort, we developed three models of developing research skills in the engineering education community through the Institutes for Scholarship on Engineering Education.

CAEE's research contributed much to the growing body of knowledge in engineering education, but there are many areas in which more scholarship is needed. To help stimulate conversations about future research needs, we generated a list of research questions. Table 1 shows a selection of these questions, categorized by topic. Some of the questions represent a direct extension of our research, and others expand beyond our work to other important and necessary areas of engineering education research.

9. Moving forward as a community

CAEE produced many research findings and developed programs across a broad spectrum of the engineering education system, including undergraduate students, graduate students, faculty, and engineering education researchers. As a center, and working with campuses across the country, we engaged in each of the elements of the Innovation Cycle of Educational Practice and Research described by Jamieson and Lohmann [54].

CAEE resources enabled an interdisciplinary team of faculty and students to study engineering education over an extended period of time and at a diverse set of institutions. The breadth of skills of the team allowed for multiple interpretations of data, the development of a variety of pictures of engineering education, and the ability to reach a wide audience. We are encouraged that the engineering education research community has grown over the course of the center and anticipate this community engaging in research on the many important challenges facing engineering education.

As Louis Pasteur famously said, "chance favors the prepared mind." As seen in CAEE's work, engineers can prepare their minds in many ways to help them recognize and make the most of the myriad opportunities and complex challenges they face today [55]. As a community, it is our responsibility as researchers and educators to engage in meaningful conversations about changing the engineering education system to ensure that our engineering graduates are as prepared as possible.

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