FREE
Future Ready Engineering Ecosystems

Preparing Engineering Students for the Future

Report of the Future-Ready Engineering Ecosystem (FREE) Workshops

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Founded in 1893, the American Society for Engineering Education (ASEE) is a nonprofit organization of individuals and institutions committed to furthering education in engineering and engineering technology. ASEE develops policies and programs that enhance professional opportunities for engineering faculty members and promotes activities that support increased student enrollments in engineering and engineering technology colleges and universities. ASEE also collaborates with national and international organizations to advance its mission.

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1.0 Executive Summary

In the context of rapid and radical changes in technology and industry, there is a pressing need to change the way we educate students for the future of work. The American Society for Engineering Education conducted a series of workshops to envision what competencies future engineers need to meet the challenges of new and different ways of living and working.

The workshops occurred in the spring and fall of 2022 and are described in this report. The first two workshops in May 2022 gathered about 50 people from various parts of the engineering ecosystem (e.g., higher education, industry). The goal was to envision what engineering might contribute to our future society, focusing on emerging technologies, such as artificial intelligence, machine learning, advanced manufacturing, quantum information science, data science and analytics, advanced communication networks/5G, biotechnology, and others. The participants in these workshops developed a taxonomy of the competencies and capabilities needed by engineers to meet the changing needs of society. The second two workshops in October 2022 gathered about 150 people from the engineering ecosystem to create action plans for changing engineering students' education to better prepare them for the future.

The Future-Ready Engineering Ecosystem (FREE) Competency Taxonomy was developed in the first convening in May and used to draft plans for change in the second convening. The FREE taxonomy is designed as a general guide on what abilities engineers need to meet future challenges. It focuses on future technologies and engineering practices, covering a wide range of competencies. The guide takes a holistic and human view of engineering based on emerging trends. As such, there is no expectation that any one individual can acquire the full range of competencies—especially in four or five years of schooling. However, it encourages educators to go beyond traditional views of what makes a competent engineer. Workshop participants believed that the future would need engineers with a broad range of abilities to collaborate and work beyond the disciplinary boundaries of engineering fields.

The Competency Taxonomy and Rubric for Action, produced out of the second convening, was developed as a general guide for change in higher education. The participants realized the complexity of such change and designed a rubric covering various levels of organization: individual, program, and institution. It is understood that educational change is not a simple process of adopting new curricula or different pedagogies; rather, it requires programmatic and institutional realignments toward a competency-based education. This is controversial across higher education. The rubric, like the competency taxonomy, serves as a map for the complex interplay of individual faculty, students, administrators, programs, and institutions. Change can begin at different points and in various ways. These are described in the rubric. It is expected that specific changes can be designed differently and no one organization can do everything all at once.

The taxonomy and rubric are starting points on the journey of changing—even revolutionizing—the way we educate engineering students for the future.

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2.0 Introduction

To assist higher education programs in adapting their practices to better prepare engineering professionals for the future workforce, the American Society for Engineering Education (ASEE) conducted a two-part workshop to identify the key competencies and potential elements of education required to prepare a future-ready engineering workforce. This project builds on the National Science Foundation's (NSF) strategic goals of growing a more capable and diverse STEM workforce, advancing the nation's scientific and innovation skills, and preparing for the projected impact of future industries like artificial intelligence (AI), machine learning, advanced manufacturing, quantum information science, data science and analytics, advanced communication networks/5G, and biotechnology.

For this project, ASEE conducted a visioning workshop to identify and articulate key competencies considered essential for future-ready engineers. The aim of this multi-stakeholder workshop was to develop resources to equip engineers with the skills needed for success in the future workplace and to increase the capacities of the nation's engineering workforce. This project's results will help define the startup phase of establishing a sustainable Future-Ready Engineering Ecosystem (FREE) composed of education, policy, and private sector collaborations, necessary to develop a competitive and world-class U.S. engineering workforce.

The objectives of the FREE workshop series were two-fold: 1) Visioning and defining key competencies, and 2) Operationalizing the competencies for use in engineering education.

The Future-Ready Engineering Ecosystem Competency Taxonomy (FREE-CoT) was formulated in the first workshop as a set of key competencies for desired student outcomes in two general categories: technical competence and personal/professional competence (see **Table 4.2**).

The second workshop used FREE-CoT to define specific actions educators, policymakers, and industry can take to co-develop a critical mass of engineers with the competencies needed to succeed in coming years. We also developed suggestions for necessary changes in engineering education to better prepare future-ready engineers. Additionally, a guiding rubric was drafted to assess changes toward future-ready engineering education.

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3.0 Preparing Future Engineers: A Brief Review

3.1 Future Engineering and Technology

As the nature of work continues to change, the competencies workers need continue to evolve. Increased use of and dependence on technologies, along with vast amounts of available data, are driving the need for increased expertise and competence in new technologies and ways of working (National Academies of Sciences, Engineering, and Medicine, 2016). Schwab (2016) claimed that the current wave of developing technologies and work processes is not simply an incremental evolution from recent increases in digitization developed since the mid-20th century, but rather a revolutionary change in the technologies emerging and the ways work will be done. It is the breadth, depth, and speed of current changes and innovations, along with the disruption of entire systems of production, management, and governance that is unprecedented. This fourth industrial revolution (4IR) will not only change "what we do, but also who we are" (Schwab, 2016, p. 6). A few of the commonly identified changes in STEM-related fields are new forms of AI; increased interconnectivity among people, communications, tools, and machines; and the explosion of data providing enhanced opportunities for understanding and decision-making (Richert et al., 2016). These emerging changes will likely have profound effects on "customer expectations, product enhancement, collaborative innovation, and organizational forms" (Schwab, 2016, p. 4).

Capturing the benefits and avoiding the risks of these advancing technologies and new ways of working will require the diligence and stewardship of people (Schwab, 2016). Therefore, changes in the future workforce's education and preparation must include a critical emphasis on human values and societal well-being. Avis (2018) examined the emerging 4IR and emphasized the risks of ideologies driving the quest for increased productivity and profits that could diminish opportunities for meaningful employment and exacerbate social injustice. Avis also noted that we do not know how these technologies and work dynamics will play out. There are individuals on both sides of the issue, emphasizing either the risks or the benefits. Schwab's (2016) claim that it all depends on people and our values turns our attention back to the importance of educating future engineers not just for technical competence, but also human competence as social citizens of the society we want to live in.

The competency model presented in this report was developed with a focus on the future and to include both technical and personal/professional competence. There have been several attempts to identify the competencies that future workers need, with several existing models. This report differs in that it describes a project to identify and articulate the competencies engineers need for the near-future—the next few decades. There are difficulties defining a competence taxonomy for the whole of engineering. First, it is not a homogeneous discipline; there are many facets or fields and specialties within engineering. Additionally, there are several different pathways for students studying in STEM fields. These different facets have unique competencies in addition to standard competencies. This effort focused on a general level of future competencies engineers need in fields defined by new and emerging technologies, as described by the 4IR (World Economic Forum, 2020) and other future technology-driven models (e.g., DeSeCo). There is variation in what these fields are; however, some commonality is found, including the fields of data science, AI and machine learning, connectivity and networks, biotechnology, and quantum information science.

4IR is described as one of the major challenges facing societies, economies, and the well-being of people around the world (World Economic Forum, 2020). The idea of 4IR (a term attributed to Klaus Schwab in 2016) describes the radical changes to our ways of working and living resulting from the new technologies and systems encompassing our lives (Avis, 2018; National Academies of Sciences, Engineering, and Medicine 2017; Schwab, 2016). These technologies are interconnecting the realms of the physical, biological, and digital, leading to imagined and uncertain possibilities by further connecting humans and machines (Rickert et al., 2016). The idea of 4IR follows three previous revolutions. The first industrial revolution was the mechanization of industry using the technologies of water- and steam-powered machines; the second was the development of mass production using technologies of electricity and the assembly line; the third revolution was the shift to computerization and automation; and the fourth is the widespread use of cyber-physical systems projected to significantly change the quality of our lives and work.

While there is a tendency to focus on technologies, Schwab and Davis (2018) insisted that we focus on the changes to our human systems that might result in improved or degraded ways of living. Risks of 4IR include exacerbating the inequities of our societies, destroying the natural environment, and losing a human-centered focus in our lives. They proposed four key principles to guide our way forward: 1) **Focus on systems** that deliver human well-being, not just on technologies; 2) **Manage technologies** with diverse human decision-making and agency, instead of giving in to a determinist view of technology; 3) **Employ human-centered design thinking,** not passive acceptance of technology as the default; and 4) **Recognize values as a core feature,** instead of perceiving technology as neutral and values as interference. Furthermore, they claimed that since 4IR is in its early stages, there is still time to address the issues and decide on the outcomes that emerge from this revolution. The World Economic Forum, having focused intently on the emerging possibilities of 4IR, considers three main values to be recognized and required in all development of technologies related to the 4IR: "preserving the common good, delivering multigenerational environmental stewardship, and holding the primacy of human dignity." (National Academies of Sciences, Engineering, and Medicine 2017, p. 2).

4IR is "linked to the concepts of digitization, automation, robotization, interconnectivity, and additive manufacturing triggered by artificial intelligence and deep machine learning, seeks to improve the productivity, efficiency, innovation, and competitiveness of manufacturing" (Loumpourdi, 2021, p. 2). In addition to the increasing benefits of new technologies, there are significant risks exacerbated by an increasing gap between those developing new technologies and the stakeholders affected by them (National Academies of Sciences, Engineering, and Medicine 2017). Thus, it is crucial to focus development on human systems and values and the common good.

4IR is one of the latest views of the future calling for "new behaviors, new orientations, new practices or new mindsets," affecting four sectors: "technology, the job market, production (factories and industries), and education" (Chaka, 2020, p. 369). The expression "4.0" has come to signify the emergence of digitization and connectivity for numerous systems (e.g., "software, smart networks, automated machines, sensors, workpieces, communication technologies, the Internet of Things, Services, and People, augmented reality, and virtual reality largely based on underlying technologies of artificial intelligence (AI), machine learning (ML), and algorithms" (p. 370)). One of the major issues related to 4IR is the education and reskilling of the workforce. Along with emphasizing technology comes developing competent technicians and engineers.

To better understand the range of work on competencies needed for the future, Chaka (2020) conducted a scoping review of the literature, finding little consensus on what 4IR actually is and what competencies its workforce needs—although some general patterns were found among the published work. Across the 69 articles Chaka reviewed, the most commonly identified competency categories were communication, creativity, and problem-solving. Regarding technical skills, programming was the predominant competency, with others like information literacy under-recognized. Overall, there was a wide range of competencies proposed by different authors from varying disciplines, indicating that understanding of 4IR and its workforce requirements are still in the early stages of development.

In other work focused on 21st century skills, the Organization for Economic Co-operation and Development (OECD) proposed four categories of skills needed by workers and citizens in the various global knowledge societies. These categories included an array of skills labeled as cognitive, intrapersonal, interpersonal, and technical (Ananiado & Claro, 2009; Geisinger, 2016). Several other models have also been presented that typically cover similar skills as the OECD model. For example, the Partnership for 21st Century Learning proposed four categories labeled as key subjects; learning and innovation skills; information, media, and technology skills; and life and career skills. The key subjects include the 3Rs and 21st century themes that support each of the other three categories sometimes labeled as learning, literacy, and life skills (van Laar et al., 2020). Across numerous competency models, emphasis is commonly placed on skills in communication, technology, information, creativity, critical thinking, collaboration, problem-solving, entrepreneurship, innovation, and digital skills.

3.2 The Nature of Competence

The challenges and demands of an increasingly complex world require people to continuously learn and develop crucial competencies throughout their lives. Across our international community, societies tend to agree that fostering and supporting life-long learning and competence development will help people live better lives, pursue sustainable development, and create a more stable, just, and peaceful world (Rychen, 2009). The idea of competence and its derived competencies is believed to be one way to help pursue societal development and fulfillment. At times, the interests and concerns of policymakers, employers, researchers, and the general public in developing a competent and learning society reflect a skeptical view of the adequacy and quality of our education and training systems (Rychen, 2009).

The idea of focusing on competence is credited to McClelland, who in 1973, argued for use of competency testing instead of intelligence or personality tests to infer performance. The idea was to identify the behaviors differentiating high performance from low performance in a particular job. Much of this work depended on a detailed and rigorous job analysis, although McClelland argued that more general clusters of competencies were more useful for modeling life or job performance (Stevens, 2012). General clusters or constellations of generic competencies tend to be favored by global societal concerns (Rychen, 2009), whereas detailed, specific competencies tend to be developed by particular organizations for managerial and legal purposes.

Early models of competencies were based on behaviorist and functionalist approaches that isolated particular observable behaviors identified as doing something proficiently or competently (Gonczi, 1994). The narrowness of this approach and its reification of intangible qualities made it difficult to apply to professional work. The interdependencies and interactivity of much contemporary work were ignored in this highly individualistic and deconstructed view of work. To overcome some of these difficulties, scholars attempted to include more generic cognitive competencies believed to support behavioral activity. These included such abilities as critical thinking, problem-solving, knowledge, and so on. These “meta-competencies” were still highly individualistic and difficult to teach, assess, and transfer to a variety of work in any meaningful way (Gonczi, 1994). From in-depth studies of professional work, Dall’Alba and Sandberg (1996) and Sandberg (2009) found important interpretive factors at play in work performance that were largely ignored by competence research and theorizing to this point.

Two important aspects of competency models include not only the articulation of competencies (what they are), but also the explanation of the process by which the competencies were identified (how they were formulated). Codifying competencies can be done by analyzing and modeling work tasks and procedures and examining past practices (Clardy, 2008). Forecasting the competencies needed in the future might also be done by anticipating future practices, often by inquiring what experts believe these practices to be in the future and developing future scenarios (Campion et al., 2011). This was the method driving the workshops for this project.

Competency modeling has become more useful in organizations than more traditional means of job analysis (Campion et al., 2011). Schippmann (1999) argued that a traditional, reductionist approach to job analysis was outdated in the 21st century, in which jobs were more self-organized, contingent, protean, non-routine, complex, and cognitive compared to the manual, behaviorist routines of the past. A more realistic view for analyzing 21st century jobs is to take a dynamic modeling approach that is more fluid, interdependent, interconnected, and systemic or ecological. Job and competency modeling are not a singular event, but rather an important part of a process of developing and managing strategic human systems that are interdependent on and embedded in other environmental and contextual systems.

Two complementary domains commonly make up the system in which competence is conceptualized and modelled: 1) The Worker (includes the competencies available from an individual), and 2) The Work (includes the competencies needed by a job, organization, or occupation) (Schippmann, 1999). The two are interdependent and necessary parts of the whole (see **Figure 3.1**).

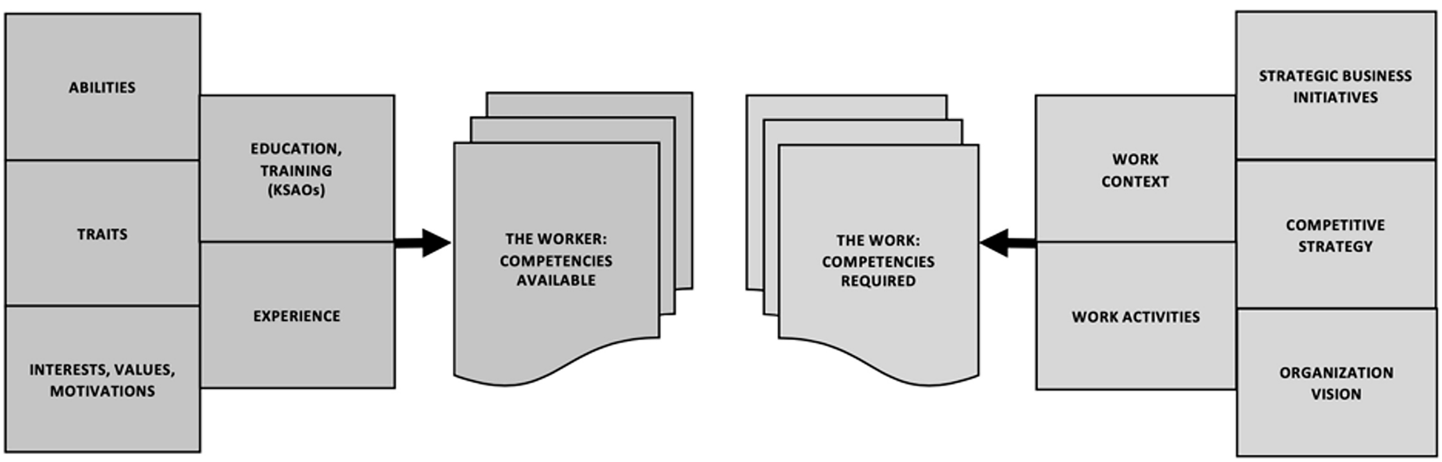

Figure 3.1 Comparing Individual Competencies Available to the Required Competencies of the Job

Source: Schippmann, J. S., 1999, Strategic Job Modeling: Working at the Core of Integrated Human Resources

Campion, et al. (2011) identified 20 best practices for competency modeling from the practitioner perspective (based on experience, not research). Three broad categories of practices included: 1) Analyzing/identifying competency information, 2) Developing a model by organizing and presenting the information, and 3) Applying/using the information/model.

Since the beginning, there has been tremendous ambiguity about, and often conflicting conceptualizations of, the idea of competencies (Barnett, 1996, 2009; Gonczi, 1994; Rychen, 2009; Dall'Alba & Sandberg, 1996; Spinks, et al., 2006, Velde, 1999), including critical perspectives that argued for a capabilities approach (Lozano, 2012). Fifty years later, little has changed to clarify this work and achieve consensus. The concepts related to competence are often used interchangeably and defined differently—if they are defined at all. This ambiguity leads to the various conceptualizations, definitions, models, and levels of specifications of competence and competencies that we find today.

To manage this ambiguity and confusion, it is important to articulate one's definition clearly from the beginning. For this project and report, the definition of competency used was based on Passow and Passow (2017), who defined competencies as, "the knowledge, skills, abilities, attitudes, and other characteristics that enable a person to perform skillfully (i.e., to make sound decisions and take effective action) in complex and uncertain situations such as professional work, civic engagement, and personal life" (p. 476). We slightly modified this definition by combining the concepts of "abilities, attitudes, and other characteristics" into the concept of "attributes," a broader, more encompassing term.

The guidelines for this project were framed by the question: **What knowledge, skills, and attributes are needed by engineering graduates to perform as competent engineers in the future?**

This question drove participants' work in the first two workshops, culminating in the FREE-CoT (see Table 2). The second two workshops considered many ways in which these competencies could be developed in engineering students. These general action plans were largely concerned with instituting a more competency-based education for engineering students.

3.3 Competency-Based Education

Competency-based education in schools and employee development in the workplace have emerged in the past few decades to guide students and professionals in enhancing their performance in many fields. While there is no common definition of competencies, competency models generally include KSAs (knowledge, skills, attitudes or abilities) and beliefs, motivations, values, interests, experience, and observable behavioral indicators that can differentiate performance levels. Competency models are sets of individual and job-related attributes leading to effective performance in particular jobs (see **Figure 3.1**). Competencies are typically developed to identify high performance (i.e., differentiate top performers from average performers) and to distinguish among employee levels in an organization (Campion, et al., 2011).

The key advantages of the competency approach were (Athey & Orth, 1999):

- The best way to understand performance was to observe what behaviors lead to success
- The best way to measure competence is to have people perform the behavior related to high performance
- Competencies can be learned and developed over time
- Competencies can be visible and accessible so people can develop them
- Competencies should be linked to meaningful life outcomes in the real world

The idea of competencies has received more attention in the past few decades. It has also been broadened from the individual level to the group and organization levels. Various competency models have been developed to represent the specialized knowledge and practices of professionals within a field (e.g., engineering, law, medicine), including the domains of personal characteristics and professional proficiencies (McAuliffe, 2006). Typically, competency models focus on the person, while job analyses focus on the characteristics of the work. Job modeling combines these two—the person and the work—to take a more holistic view of the contextual factors that contribute to high performance on the job (Schippmann et al., 2000).

However, there remain critics of creating and using competency models—especially in professions characterized by high levels of uncertainty, complexity, context sensitivity, judgment, and tacit know-how. Critics often point out that competencies are not neutral or objective. Competencies are designed from a point of view and used to judge others' abilities as a way of distributing power to the competent. They are also a way of placing responsibility on the learner to improve (Solomon, 2001).

Learning has taken on new relevance in organizations and professions as a means to develop high performance and competitiveness. Learning has also been a way of building competencies in people, organizations, and professions. The value of a competency-based framework is its focus on learning and development (Solomon, 2001). Professional competence is not the routine application of technical knowledge, but rather it is the use of evidence-based decisions that emerge from multiple views. It is a reflective capacity linked to higher levels of development (post-conventional thinking). Other descriptions of professional competence include a high level of autonomy that promotes action aligned with self-defined principles, self-acceptance, and freedom from what others think. It includes an openness to other views (non-defensive), reflection on contextual and cultural beliefs, and flexibility conducting tasks (McAuliffe, 2006).

Regarding the organization and prioritization of various competencies in engineering curricula, Passow and Passow (2017) provided three organizing principles: 1) The work of engineering encompasses technical and social activities—both are essential to the success of engineering; 2) Non-technical competencies cannot be taught effectively in isolation from the technical work; and 3) Engineering education would benefit from a stronger connection to engineering practice. These principles emphasize important requirements for the preparation of engineers in the 21st century.

Current trends affecting the evolution of competency methods in business and organizations are changing. The scientific approach to competency modeling (assigning high performers to one group and average performers to another to analyze significant behavioral differences) is giving way to a participative approach more aligned with open and participative organizations. To adapt more quickly to the increasing pace of change, managers need faster ways of identifying and developing competencies. They must shift the focus from identifying and describing competencies based on past performance to identifying emerging competencies needed in the future. Traditionally, the individual has been the unit of analysis for competency modeling and thought to be the source of organizational performance. Currently, the unit of analysis in organizations is increasingly on team and group processes. Thus, understanding and developing team and process capabilities is critical. Additionally, sourcing people with diverse competencies has led to the growth of virtual teams that draw together experts from a variety of locations. New competencies for virtual work are needed. Developing and enhancing organizational and process competencies helps people solve problems, experiment, learn, and combine and leverage their individual competencies with others (Athey & Orth, 1999).

Specific to engineering education, Froyd, Wankat, and Smith (2012) identified five major shifts in engineering education over the last 100 years—each entailing differences in the competencies required of students. Competencies evolved from practical knowledge and skills in the early 20th century to science-driven models of knowledge and skills towards mid-century. The next three shifts are concurrently in progress, as engineering education focuses on the design sciences, learning sciences and outcomes, and information, communications, and computation technologies changing education, work, and societies now and into the foreseeable future.

Competency models in engineering have evolved beyond traditional scientific and technical skills to include professional skills (also known as “soft skills” or social skills) and personal characteristics that support high-performance engineering work. For example, the ABET Engineering Accreditation Commission changed to an outcomes-based model that focused less on engineering knowledge and more on what engineers should be able to do upon graduation. The student outcomes (Criterion 3: 1-7) include the abilities to apply technical and scientific knowledge, conduct experiments, formulate systems, function on teams, communicate effectively, understand social and global impacts, comply with professional and ethical responsibilities, and engage in lifelong learning (ABET, 2021).

Two other current examples of engineering competency models were developed by the American Association of Engineering Societies (AAES) and Collegiate Employment Research Institute (CERI). The AAES model developed by AAES and the U.S. Department of Labor has six categories of competencies, starting with personal effectiveness, followed by academic excellence, workplace skills, technical competencies, and discipline- and job-specific competencies (American Association of Engineering Societies, 2016). Two of these categories explicitly refer to job and workplace competencies. The Collegiate Employment Research Institute (CERI) at Michigan State chronicled employer expectations from thousands of job postings and surveys since 2003. In addition to the basic technical competencies, employers want candidates who can develop effective working relationships, communicate well, learn continuously, manage a project and team, coach and mentor others, analyze and interpret data, and understand the local and global impacts of company practices (Hanneman & Gardner, 2010).

Overall, there is controversy about developing the professionals' competencies. Some believe that school is not the place for narrowly conceived vocational and behavior-based skills development but rather the time for students to develop their knowledge, values, insights, and judgment broadly and freely—factors critical to a professional life. Critics charge that a competency-based education hampers the development of thoughtful, insightful, empathic professionals having good judgment (Morcke, Dornan, & Eika, 2013; Passow & Passow, 2017; Talbot, 2004). Others believe that engineering is an applied field, and students should develop skills that focus on the application of knowledge. A more current and holistic view of knowledge application includes developing thoughtful, empathic individuals along with the social, cultural, and political skills in use broadly in professional organizations and communities worldwide (Passow & Passow, 2017).

Hager (2004) pointed to weak assumptions about learning that support the proponents (and opponents) of a competence approach. These assumptions include "folk beliefs" that learning is individualistic, replicable, and about knowledge and skills that are stable and enduring, and that there is one best way to learn. The assumption that learning is a product acquired through study and teaching is also arguable. Three concepts are not clearly understood: 1) Performance outcomes are about the results of specific processes, not representative of knowledge and skills; 2) The typical elements of competence (e.g., knowledge, skills, abilities) do not represent all that goes into competent performance; and because of the misunderstandings of these two, 3) Educating people to be competent is incomplete and fragile at best (this does not mean we should give up on competence education, but rather know that our understanding and work is uncertain).

An important factor that is usually overlooked in different skills frameworks is its design context. Whether it is a particular national or regional context; specific to developmental categories of nations; focused on particular disciplines, industries, professions, workplaces, social classes, or technologies; or focused on facets of life in general (e.g., work, school, family), the context is an important framing undergirding any competency model. To address this broad and diverse landscape, Joynes and colleagues (2019) suggested that "rather than generating another framework of definition in an already diverse and potentially crowded field, it is suggested that any institution seeking to engage with 21st century skills programming in a range of global settings should instead adopt whichever pre-existing model provides users with the most flexible and outputs-orientated framework" (Joynes, et al., 2019, p. 20).

Many existing competency models fall short on technical competencies in an engineering context—especially for future needs. The focus of this project was to develop a competency taxonomy for engineering practice that emphasizes new and emerging technologies, such as AI, machine learning, advanced manufacturing, quantum information science, data science and analytics, virtual/augmented reality, advanced communication networks/5G, and biotechnology. We built upon existing knowledge of engineering competencies and added additional competencies as needed. Since many non-technical competencies are essential to engineering practice, we included the personal and professional competencies that make up a holistic engineering competency taxonomy (see **Table 4.2**).

Because the concept of competencies is challenging and built on competing views, we consider competencies to be heuristics, or general guidelines for action. Competencies are not concrete items or formulas that can be taught or acquired without consideration of myriad contexts and debate. The competencies in this taxonomy are intentionally general to have broad applicability across many fields of engineering and technology (Rychen, 2009). This general approach is especially relevant to engineering education, which prepares engineering students for different career paths in engineering and beyond, as well as for an uncertain future.

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4.0 Convening the Workshops

4.1 Preparation

Design and Development of the Program

Recognizing the need to adapt institutions of higher education to the emerging needs of the Future Industry (FI) workforce, ASEE proposed a two-part workshop series to identify the key competencies required for a future-ready engineering workforce and the elements of an education action plan that would equip the workforce. This proposal built on NSF's strategic goals of fostering the growth of a more capable and diverse research workforce and advancing the nation's scientific and innovation skills, and on prior work.

The proposed Future-Ready Engineering Workforce workshop series was an extension of the TUEE initiative, focusing on a specific subset of key "future-proofing" competencies. Conceptions of what society values under specific socioeconomic and political conditions influence how key competencies are defined and selected. Thus, we noted the need for new visioning to identify and disaggregate key competencies with enough specificity to convey meaningful change actions in the education sector.

The first proposed workshop focused on disaggregating key competencies for the future-ready engineering workforce. It identified a prioritized taxonomy of the disaggregated key competencies with essential details and context summaries to provide meaningful specificity. This FREE-CoT then became the desired student outcomes for the second workshop.

The second workshop built upon the outcomes of the first to define the specific actions educators, policymakers, and the industry need to take to co-develop a critical mass of emerging engineers with the competencies needed to succeed in the coming years. A framework for the necessary changes in each sector was identified along with the required actions to achieve these changes. The framework also included the essential collaborative processes that must be established across the sectors to achieve the communication and feedback required for ongoing co-development. A rubric was drafted that defines a threshold of what success looks like for each key competency. This Future-Ready Engineering Ecosystem Framework and Rubric for Action (FREE-FRA) can now provide an easily communicated vision for a national call to action.

Selection and Recruitment of Participants

On April 8, 2022, an invitation was sent to a list of potential participants in the project. The invitation announced NSF's funding for this project and described the meeting objective: identify "the critical competencies required for a future-ready engineering workforce for the Industries of Tomorrow: Quantum, Spectrum, AI, Cybersecurity, Biotech, and Advanced Manufacturing; and the elements of an education action plan that would equip such a workforce." The invitation encouraged those interested in this project to learn more on the ASEE website, "Defining and Building the Engineering Workforce of the Future," at free.asee.org. An acronym, FREE, was created representing the "Future-Ready Engineering Ecosystem."

Participants were selected based on nominations from the FREE Advisory Board and Honorary Chairs. The nominees were chosen to represent practitioners, employers, innovators, and policymakers related to the development of a future-ready engineering workforce.

Of the 52 participants, 62% were male and 38% were female (see **Figure 4.1**). The participants brought their insights from 16 areas of expertise (see **Figure 4.2**). While the majority came from academia, the group also represented other employment sectors (see **Figure 4.3**).

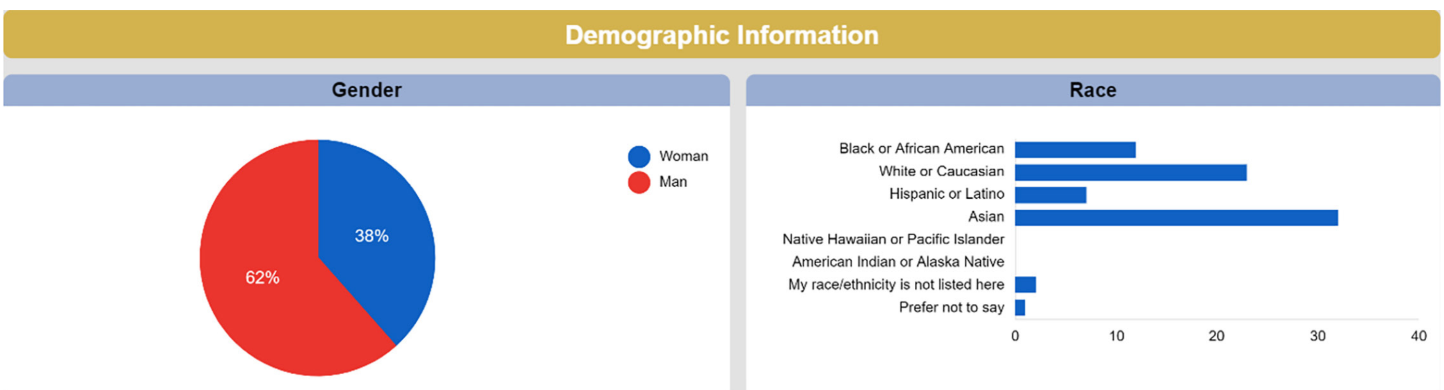

Figure 4.1 Demographic Information from First Convening Participants

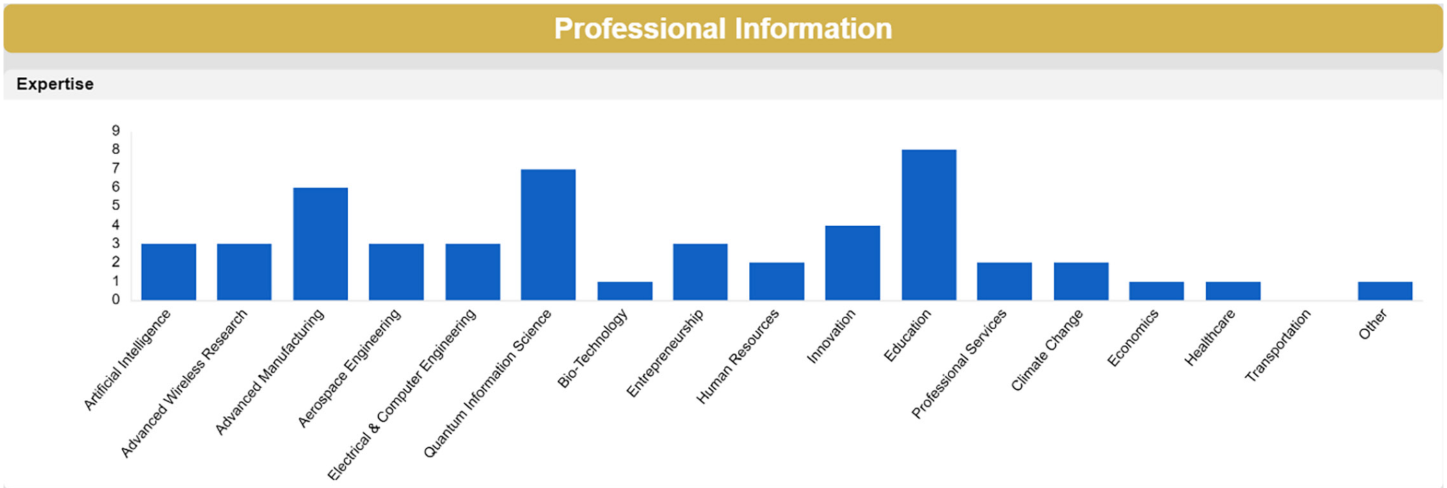

Figure 4.2 Participant Expertise

Figure 4.3 Professional Sectors

4.2 First Convening: Pre-Work to Gather Ideas on Future Societal Challenges

Prior to the first meeting on May 17, 2022, the participants were asked to submit future issues in our societies that might need engineering solutions.

A few examples of the submitted issues were:

- How might we ensure the sustainability of our oceans?
- How might we balance sustainable development with global climate change? Moving towards steady-state economics over growth-based economics.
- How might we improve social justice?
- How might we overcome hate and fear?
- How might we ensure access to healthy food and food sustainability?
- How might we improve access to health care for all?
- How might we address issues of disability?
- How might we ensure critical infrastructure resilience in the face of climate change?
- How might we achieve equitable access to technology and information?

These statements, along with 63 others were sorted and synthesized into six Major Societal Challenges:

1. Climate change
2. Social justice and mobility
3. Access to food and water
4. Health care
5. Infrastructure and transportation
6. Information technology
7. Artificial intelligence
8. Machine learning

4.3 First Convening: Day One (May 17, 2022)

The first day began with an introductory meeting of the Advisory Committee and mentors. This discussion revisited the project's goals and elaborated ways of thinking about achieving them, such as:

- The role of the mentors is not to be the expert resource but rather to encourage and guide the group towards project outcomes; to ensure that people in the group understand the problem space; and to ensure that people in the group have stretched, have looked at the questions broadly, and proposed ideas that were far and wide related to the issue.
- The remainder of the pre-meeting focused on the agenda (see **Figure 4.4**), which included introductory remarks and activities.

The objectives for Day One were to:

- Explore different perspectives in the session, including provocative stimuli
- Generate "future headlines" about likely societal challenges (group activity)
- Begin to identify the role engineers might play and what capabilities they need to address those challenges

Tuesday, May 17

12:00 - Welcome

12:30 - Scope the challenge

1:00 - *Break*

1:15 - Future Headlines

2:30 - *Break*

2:45 - Identify Needs

4:00 - *Close*

Figure 4.4 Day One Agenda

The meeting began with a video-recorded welcome and statement of the project goals by the Program Director, **Dr. Kemi Ladeji-Osias** from NSF. Her challenge to the group was to boldly envision the future of more inclusive engineering and the competencies needed to get there.

Dr. Jacqueline El-Sayed (ASEE, Principal Investigator) followed, explaining the project's purpose to focus on the industries of tomorrow and envision the KSAs (competencies) needed to meet future engineering challenges.

As the co-chairs of the project, **Dr. Maria Klawe** (President, Harvey Mudd College) and **Dr. Jeff Wilke** (Chairman & Co-Founder, Re:Build Manufacturing) emphasized that the future demanded more than the traditional practices of educating undergraduate engineering students. Everyone would need to embrace new ways of learning from and understanding new technologies, as well as within our educational system, even going beyond engineering.

Toby Scott from Knowinnovation, Inc., facilitated the session after the introductory remarks. The first two days (May 17 & 24) were focused on the "what" of the problem. This was to better articulate what the future of engineering might be and to identify specific competencies and capabilities needed to fulfill this promise. He reminded everyone that we (the participants) were the experts recruited to bring a "user" perspective to future challenges.

Scott encouraged participants to "stay in the problem" (the what) and resist the temptation to jump to solutions (the how). He asked the groups to be "properly ambitious" and divergent in their thinking, using "how might we…" prompts (e.g., How might we better solve a particularly challenging problem in the future?).

Day One - Activity 1: Challenges & Needs

To begin the work, participants broke into smaller groups to review the challenges and needs they submitted as part of the pre-work. These were sorted roughly into eight clusters based on major societal challenges identified in the pre-work:

1. Climate change
2. Social justice and mobility
3. Access to food and water
4. Health care
5. Infrastructure and transportation
6. Information technology
7. Artificial intelligence
8. Machine learning

Participants reviewed the clusters of statements, discussed them, and created additional statements, which they added to the list.

Day One - Activity 2: Future Headlines

Following their discussions of the challenges and needs, participants were assigned with the task of generating a visionary headline from the future that addresses one of the eight challenges identified above. The participants were instructed to choose either a scientifically oriented headline that might appear in a future issue of Scientific America or a popular-press sort of headline that might appear in a future issue of TIME magazine (see **Figure 4.5**). Participants could also write a few lines of copy that might be the opening of such a future article.

Scott provided a few prompts for this activity, encouraging participants to think about the major societal challenges identified earlier and what the best possible headline in the year 2035 might be announcing news that we are successfully overcoming one of these challenges using new technologies, such as quantum, spectrum, AI, advanced manufacturing, or biotechnology. Scott challenged participants to come up with a bold and audacious headline. In addition, participants were asked to add a photo and a brief paragraph elaborating the headline. The mentors joined the groups for this activity. When finished, someone from each group presented their headline (see **Table 4.1**).

The participants were fully engaged and enthusiastic about the challenge to think boldly about the value of engineering in confronting major societal challenges. At the end of the presentations, Scott expressed his amazement with the work and exclaimed, "How on earth are we going to do all this?"

During a brief discussion among the mentors after the presentations, an overall comment noted the "intense humanity" apparent across the headlines and copy. It appeared that the technologies were relegated to the background in most examples, serving to support the main message that major challenges people face around the world were being resolved for the benefit of all. Further conversation concluded that the work of the small groups showed a useful way of thinking about future engineering solutions as the 3Is: **Innovations** were new by repackaging from existing technologies; **Integrations** were skillful combinations of the technical and the human (social); and **Implications** recognized the often overlooked and unintended consequences of technology.

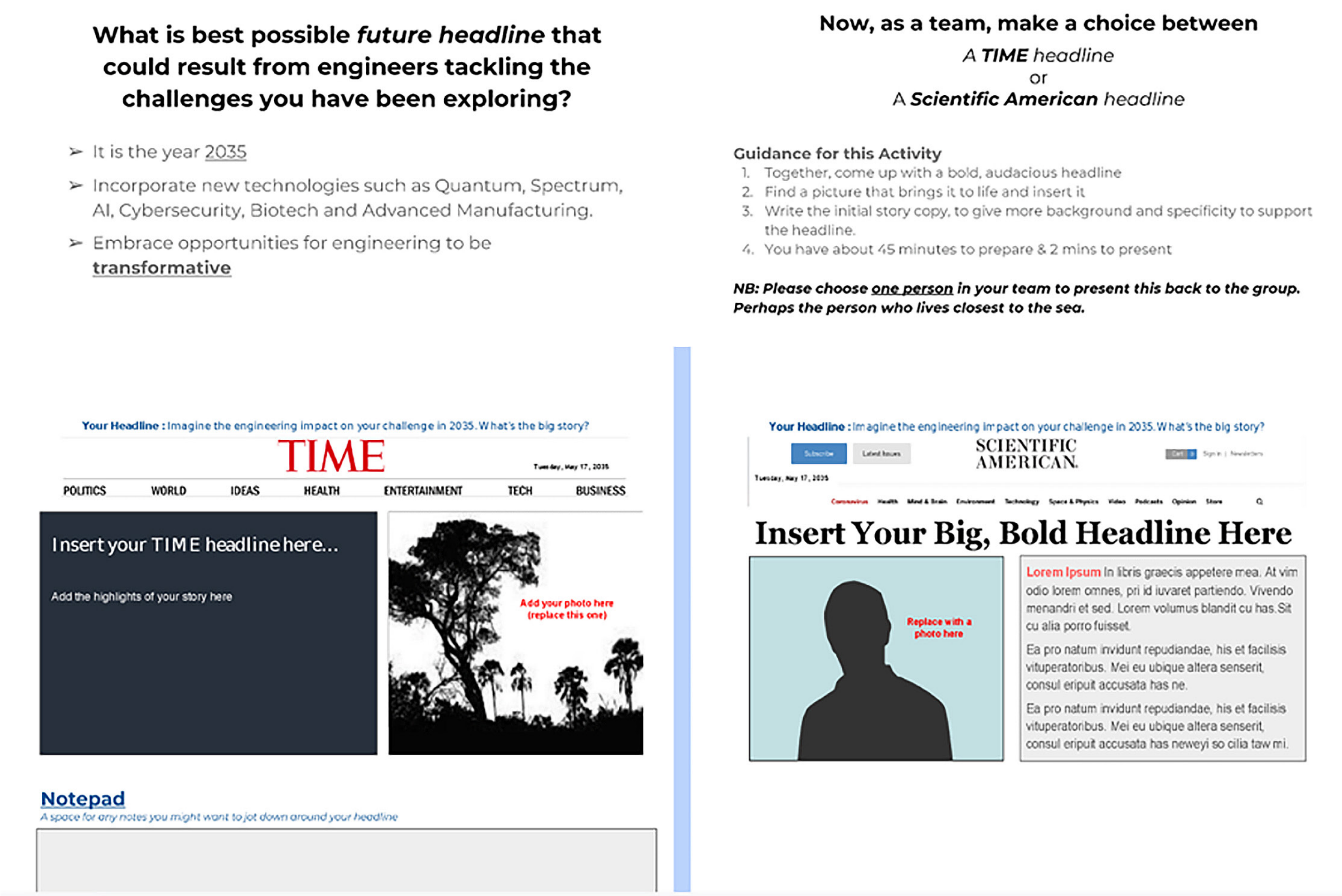

Figure 4.5 Template for Future Headlines

Table 4.1 Future Headlines Created by the Groups

Group	Headline
Group 1	Carbon-eating bacteria drop sea level two feet in Fells Point
Group 2	How one of nature's oldest biological processes is solving climate change in Detroit
Group 3	Defying expectations, technologies enable creation of a truly equitable society
Group 4	Technology and policy innovations provide resilient food and water supplies despite historic global disruptions
Group 5	Prick your finger, live to 100
Group 6	The end of illness?
Group 7	Immortality for $9.99?
Group 8	The AI digital docent has arrived

Day One - Activity 3: Identify Future Needs

After a short break, participants returned to small groups to identify what education or training needs might be required if we were to accomplish the news announced in the headlines. The groups identified a wide range of behaviors, capabilities, and skills needed by future engineers and posted these for all to see. The list grew in real time, eventually having 117 ideas. Participants could also post comments on each idea. Before the next session, the list of behaviors, capabilities, and skills was roughly sorted into three capability categories: technical, professional, and personal.

Observations from one of the breakout groups (Group 2) found participants discussing key changes in the ways we currently educate and prepare engineering students for their careers after graduation. For example, one broad topic discussed related to the design of products, technologies, and solutions. Participants addressed issues of complexity in the social space, noting that products and solutions could not be designed anymore without strong empathic consideration of the human element. Framing problems must integrate people into the frame and attend to the impacts or consequences on people and the environment. Complex problem-solving is more than technical problem-solving. Engineering solutions have typically underappreciated important dimensions of a problem, especially the human and non-engineering dimensions. Other comments recast the concept of the problem itself, redefining a problem from a technical frame to a broader human and environmental frame, as well as from a simple system frame to a complex adaptive system frame. The notion of defining a problem was being reframed. Additionally, there were questions raised about the nature of ethics and who decides what is ethical, as well as the need for humility, self-doubt, and challenging our assumptions.

The small groups reported out on their discussions that addressed ideas related to what engineers and engineering will need to be successful in the future. Some examples included the need to:

- Go beyond the traditional training for technical products to dealing with problems that were more adaptive
- Realize that the relationship between the engineer, the technology, and the problem will likely change, not only in the future but also in the present (i.e., adaptive problems)
- Emphasize trust and mentoring in the educational system
- Overcome the extreme specialization in the current educational system in favor of more interdisciplinary, collaborative work

- Emphasize more than technical competence by including an innovative/entrepreneurial mindset, cultural understanding, human behavior, and a recognition of the societal consequences of engineering work
- Have individual and collective competence
- Develop fluency across boundaries
- Develop complex identities
- Go beyond the focus of "what company do I want to work for" to "what societal problems do I want to work on?"
- Develop broad and deep capabilities in self and students
- Inspire passion in students
- Operate within a scope of ambiguity or the absence of discrete boundaries

Post-Session Debrief

After the session with the participants, the mentors met to debrief and discuss the results. Overall, they noted that the group conversations went far beyond the typical competencies or KSAs proposed for engineers (i.e., knowledge, skills, attributes). The discussion had more emphasis on the human aspect of engineering work. Other comments from mentors and the core team noted that engineering education is not a monolithic practice, but rather is practiced differently across schools. There have also been many past efforts to identify what is needed by engineers and engineering in the future. This observation led to the suggestion to add to what has already been done, to look forward not backward, and to focus on the new and positive, not remedial interventions.

Intersession Planning Meeting

The second day session with participants was scheduled for the following week on May 24, 2022. In between, the core team discussed what was accomplished on the first day and what should be by the end of the second day. A key objective for these first two sessions was to have a framework of competencies/capabilities drafted for the second convening in the fall. As a reminder, the first convening was to identify "what" is needed for successful engineers in the future and the second convening was to figure out "how" to achieve this in preparing future engineers. We discussed the need to have a competency framework/taxonomy by the end of the next four-hour session on May 24, 2022.

Feedback from the mentors and core team affirmed that we want to attend to the existing work on engineering competencies and focus more on the novel aspects of future competencies that participants mentioned. The ideal model for this project would build upon the foundational competencies of engineering and visualize the new roles envisioned by the future of engineering work. This would appear as blending the typically technical competencies foundational to engineering with the human competencies required in the future.

A second planning meeting between the two sessions focused on the activities in which the participants would engage to create the desired framework. The first planned activity was to visualize and personalize a future engineer by creating a persona. A persona represents the public image and/or social role of a fictional character that is a composite of several attributes found or desired in a particular role. Personas are used to help bring a particular identity to life to enhance understanding. This activity would prepare the participants to articulate the competencies and capabilities needed for creating the framework.

The terms used in the field and in the literature related to competencies, capabilities, and skills are notoriously confusing and inconsistent. It was recognized that clearly defining our terms was essential to developing a framework by the end of the next session. To accomplish this, we adopted the following abbreviated definitions based on the literature:

- Competencies are KSAs that individuals acquire to perform their work or role
  - Knowledge is what one knows (i.e., What I know)
  - Skills are what one can do (i.e., What I do)
  - Attributes contribute to who one is (i.e., Who I am)

In addition to KSAs, we placed competencies into three standard categories: 1) technical, 2) professional, and 3) personal. As an aid to developing the competency framework, we created a template that would help the participants focus and organize their ideas around the three categories and in KSA sub-categories (see **Figure 4.6**).

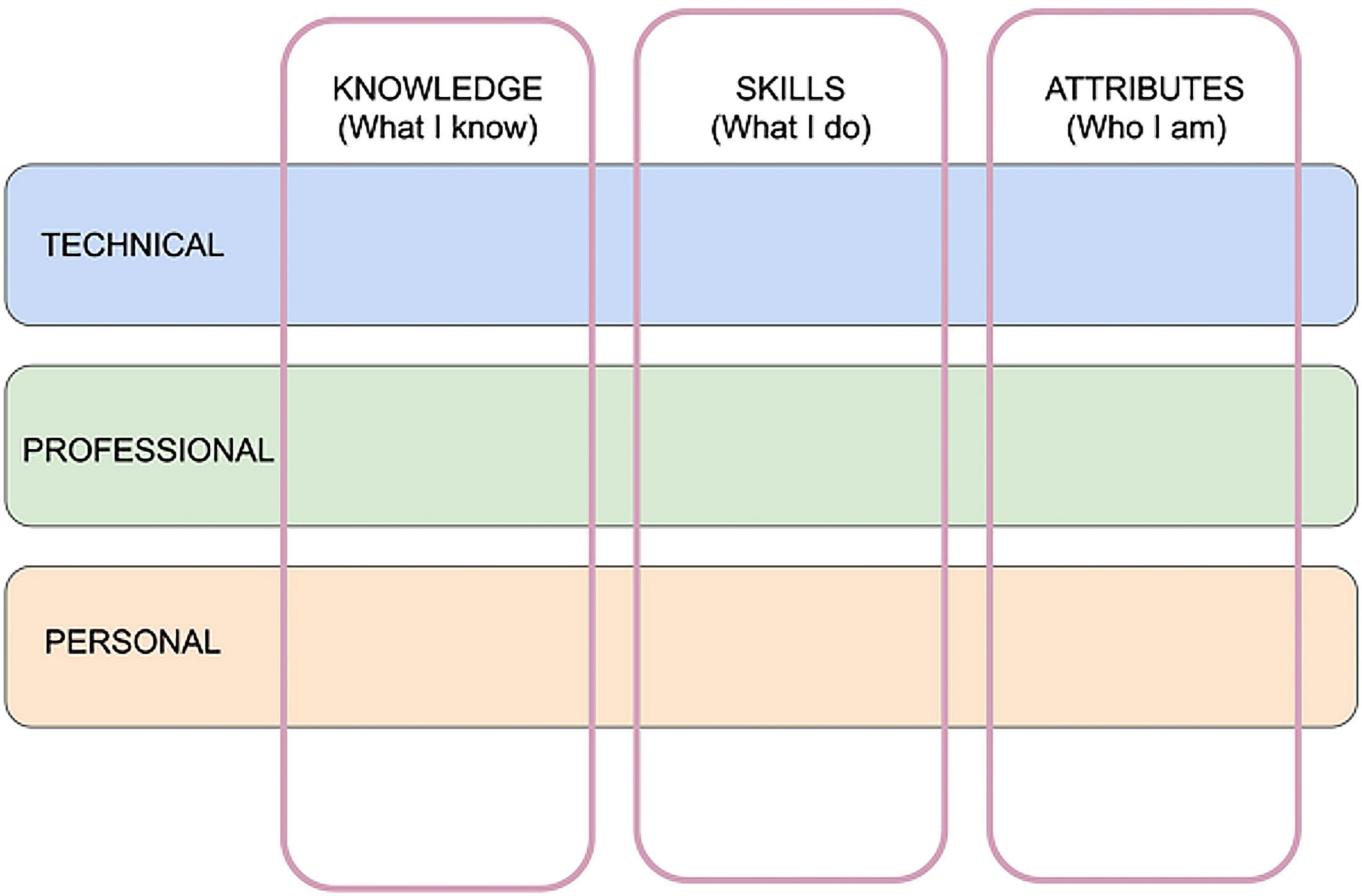

Figure 4.6 Matrix Template for Identifying Competencies

4.4 First Convening: Day Two (May 24, 2022)

The second day began with a pre-meeting of the core team and mentors to preview the day's work. The agenda included two main activities: develop personas and develop a framework (matrix) of competencies/capabilities (see **Figure 4.7**). Introductory remarks welcomed the participants to the second day and provided an overview of the day's work. The co-chairs, Dr. Maria Klawe and Jeff Wilke, reiterated that this project provided the group a chance to envision the "perfect future engineer" and to articulate what makes them perfect. Toby Scott (facilitator) reminded the participants to revisit the KSAs identified in the earlier session and in the pre-work as they engaged in their work.

Tuesday, May 24

12:00 - Welcome

12:20 - Develop Personas

1:05 - *Break*

1:15 - Play back personas

2:00 - Develop Matrix

2:30 - *Break*

2:40 - Refine Matrix

4:00 - *Close*

Figure 4.7 Day Two Agenda

Day Two - Activity 1: Develop Personas

Participants were divided into six small groups and assigned to develop the persona of a future engineer. The mentors and core team members were also assigned to different groups as observers. Guidelines for this activity and a template for representing each group's persona were provided (see **Figure 4.8**).

The participants were reminded to develop their personas of a future engineer from a global perspective and to emphasize diversity, equity, and inclusion. Additional guidance included naming the persona, giving a brief description of their background and experience, and identifying three competencies/capabilities they have in each category: technical, professional, and personal.

Observations from one of the small groups (Group 6):

- Participants introduced themselves and gave a short synopsis of their experiences
- As work on the personas began, suggestions were made about describing a particular character and different names
- The group settled on a female, person of color, with a neutral name (Adrian), coming from an underserved background
- Additional qualities included generational differences, independent and entrepreneurial nature, and having collaborative and interdisciplinary preferences
- Some of the participants referred to the "future headlines" produced on Day One
- It was apparent that suggestions for the persona were grounded in the individual participants' backgrounds and identities

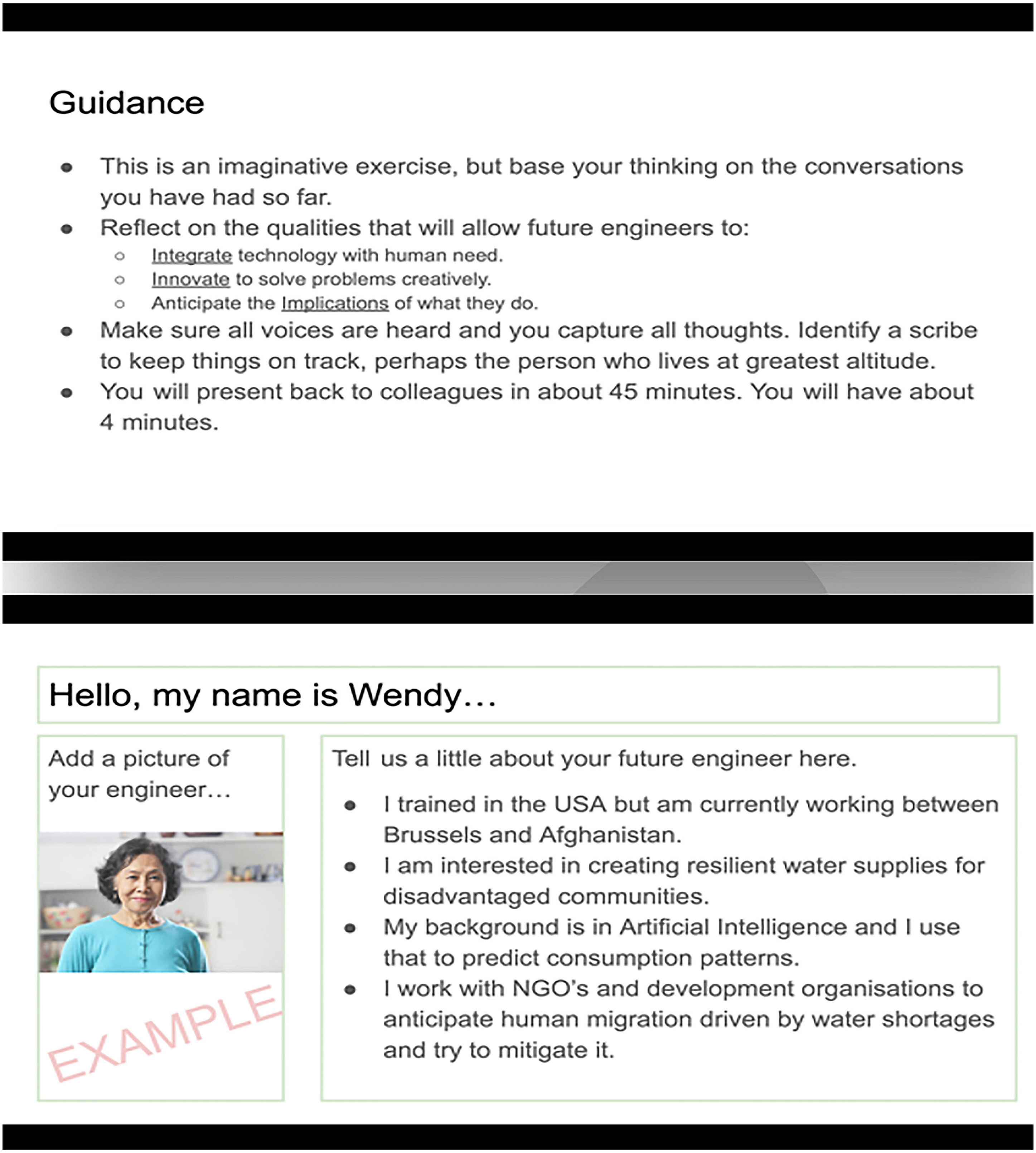

Figure 4.8 Template for Personas

The participants worked for 45 minutes on this activity and then returned to the large group to present their persona, including the list of key competencies. Each small group (6) presented their persona to the larger group. Some of the groups explicitly referred to a future headline and built their persona from the story of the headline.

There were several interesting comments across the presentations that indicated some of the depth and breadth of the discussions that occurred in the small groups. The presentations mostly described the qualities of their persona without much explanation about why they chose those qualities. For example:

- One group reported that they emphasized broad abilities that drew from outside engineering
- It was important for engineers to be able to effectively communicate with the "common person"
- A tough life experience can drive people to commit to changing a particular social condition
- Important capabilities were project experience, community interaction, collaboration, and "wrangling data"
- Storytelling was an important capability
- Some mentioned it was hard to limit their descriptions to three competencies per category (technical, professional, and personal)

More common competencies across the groups were collaboration, empathy, multi-disciplinarity, global perspectives, and community interaction.

Day Two - Activity 2: Develop Competency Matrix

The second activity of the day was designed to develop a more in-depth matrix of competencies required for a future engineer. Participants were instructed to further articulate and elaborate on the qualities they identified in the persona activity, especially those that were different from the qualities of engineers today. They were also reminded to consider the 3Is as a guiding focus of future engineering (*Integrate* technology with human needs; *Innovate* to solve problems creatively; and anticipate the *Implications* of what they do). They were divided into nine small groups, each assigned to work on a single cell of the matrix (see **Figure 4.9**).

The matrix was designed to organize the complex ideas of competencies into a useful framework or competency map. This was to be the final output of the first convening that would be the starting point for the second convening in October 2022.

Each of the nine small groups presented their work to the large group and the audience had the opportunity to make suggestions via the online platform. For each cell of the matrix there were two buttons available to the audience for feedback: one for *building* upon the work presented, and one for *concerns* about the idea(s) presented.

At the end of all presentations, the participants were asked to go back to their groups and refine their work based on the audience's feedback.

Between the first and second convening, we gathered all data from the competency matrices and synthesized it into a competency taxonomy. This was done in collaboration with the PIs, the Advisory Committee, and a brief review of the literature. We noted that there was a gap in the technical competencies. We agreed to interview a few experts in industry to help fill in specifics on technical competencies they expected and needed from future engineers.

We also received suggestions from several participants and incorporated many of those into the taxonomy. Version 7 is the latest of the taxonomy as of the date of drafting this report (see **Table 4.2**); it is still open to revisions and development.

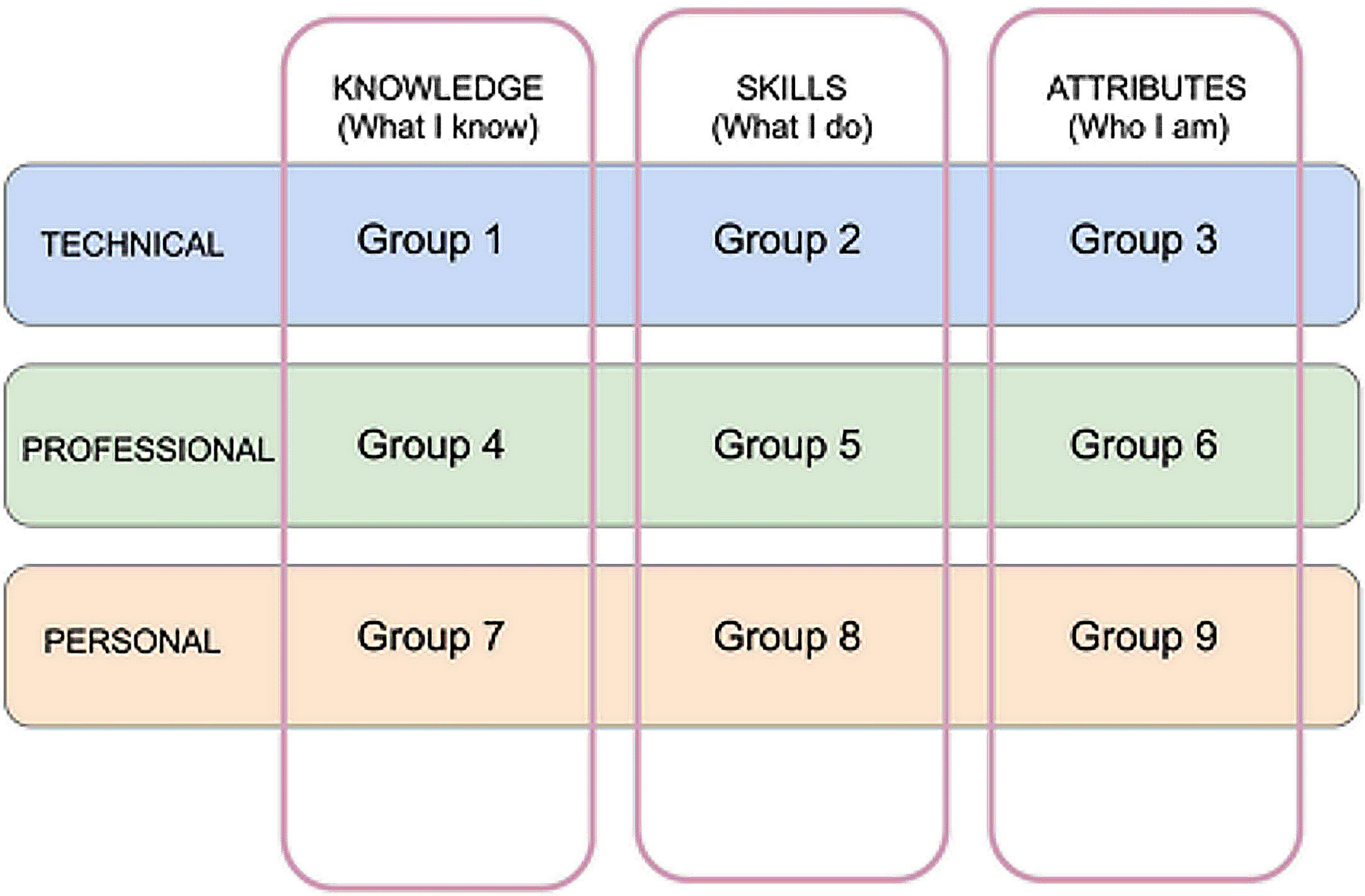

Figure 4.9 Template for Competency Matrix

Table 4.2 Competency Taxonomy (v.7)

TECHNICAL COMPETENCE: Characterizes a person as competent in a particular field of knowledge/technology (e.g., engineering)

1. TECHNICAL KNOWLEDGE
What you know and understand...

1.1. Know and understand emerging fields in engineering, including theoretical and practical knowledge of...
- 1.1.1. Data science, computer science, big data analytics
- 1.1.2. Artificial intelligence, machine learning, robotics, advanced manufacturing, automation, cyber-physical systems, cognitive agents, virtual and augmented reality
- 1.1.3. Connectivity, networks, integrated systems (iot, ios, iop), cloud computing, systems thinking, systems architecture, cyber-security, semiconductors
- 1.1.4. Bioengineering, biotechnology
- 1.1.5. Environmental engineering, climate science, sustainable materials
- 1.1.6. Quantum information science and technology

1.2. Know and understand existing fields in engineering, including theoretical and practical knowledge of...
- 1.2.1. Engineering sciences: mechanical, civil, electrical, chemical, systems, and industrial engineering
- 1.2.2. Design science
- 1.2.3. Systems science and systems thinking

1.3. Know and understand perspectives of multiple disciplines, stakeholders, and communities
- 1.3.1. Cross-disciplinary, organizational, environmental, and community issues
- 1.3.2. Leverage STEM expertise in multiple areas

1.4. Know and understand practical reasoning
- 1.4.1. Experiential knowledge, intuitions, biases, creativity
- 1.4.2. Natural decision-making, sense-making
- 1.4.3. Contextual understanding (business, economics, organizations, environment)

2. TECHNICAL SKILLS
What you can do...

2.1. Manage and perform the work of emerging technologies and engineering fields
- 2.1.1. Use, monitor, and control technologies
- 2.1.2. Design and enhance technologies
- 2.1.3. Model various systems and processes

2.2. Manage, model, and process data to create meaningful information and knowledge
- 2.2.1. Process data (envision, collect,analyze, evaluate, create, and synthesize)
- 2.2.2. Interpret, critique, and apply data-based knowledge for decision-making, quick responses, improved productivity, higher quality products, services, and solutions

2.3. Design, conduct, and communicate technical and scientific information
- 2.3.1. Collaborate in team science
- 2.3.2. Work with automated research workflows (ARWs)
- 2.3.3. Communicate with multiple stakeholders

2.4. Design solutions for people and planet
- 2.4.1. Develop creative, innovative, and intuitive solutions
- 2.4.2. Commercialize solutions and disseminate to professions and society

2.5. Design for sustainability
- 2.5.1. Use resources effectively and practically
- 2.5.2. Consider consequences of decisions

2.6. Design, change, and integrate multiple systems (technical, human, business/financial)
- 2.6.1. Analyze, improve systems, reduce risks
- 2.6.2. Effectively use tools and data

2.7. Manage multi-disciplinary projects
- 2.7.1. Apply PMI processes and engineering expertise
- 2.7.2. Lead teams, people, stakeholders
- 2.7.3. Manage project constraints
- 2.7.4. Meet goals and objectives

Table 4.2. Competency Taxonomy (v.7) (continued)

3. TECHNICAL ATTRIBUTES

Who you are…

3.1. A Scientist-Engineer

- 3.1.1. Curious, creative, innovative
- 3.1.2. Disciplined, analytical, evidence-based
- 3.1.3. Experimenter, explorer, inventor

3.2. A Problem-Solver

- 3.2.1. Realistic about constraints
- 3.2.2. Analytical, insightful, and decisive, even in uncertain situations
- 3.2.3. Adaptable and flexible
- 3.2.4. Action-oriented
- 3.2.5. Motivated to transfer knowledge/solutions to society

3.3. A Project Manager

- 3.3.1. PM process and technical expert
- 3.3.2. Leader, partner, manager, team player
- 3.3.3. Effective communicator and collaborator with multiple and diverse partners and stakeholders

PERSONAL/PROFESSIONAL COMPETENCE: Characterizes an individual as a competent, well-rounded person and professional (e.g., engineer, professional, group/organization member, community member, citizen)

4. PERSONAL/PROFESSIONAL KNOWLEDGE

What you know and understand…

4.1. Knowledge of general and multi-disciplinary knowledge

- 4.1.1. Humanities, psychology, sociology
- 4.1.2. Business, management, organization behavior

4.2. Knowledge of global, cultural, and societal issues

- 4.2.1. How different people/ communities perceive and experience issues
- 4.2.2. Interpersonal/social interactions, group dynamics, and relationship building
- 4.2.3. Ethics in work and community
- 4.2.4. Legal issues and human rights

4.3. Know and understand oneself

- 4.3.1. Awareness and understanding of personality and personal biases, limits, strengths, weaknesses, and emotions
- 4.3.2. Understand one's positionality and privilege in social hierarchies and how power structures affect relationships, decisions, and contexts
- 4.3.3. Understand and apply complexity and dialectics over simplistic, dualistic thinking
- 4.3.4. Develop and commit to thriving in health and well-being stakeholders

Table 4.2. Competency Taxonomy (v.7) (continued)

5. PERSONAL/PROFESSIONAL SKILLS

What you can do...

5.1. Continuously learn and explore

- 5.1.1. Seek new experiences and knowledge from diverse sources
- 5.1.2. Apply education and experiences to various industries, communities, and institutions
- 5.1.3. Apply critical thinking, analysis, and creativity
- 5.1.4. Use continuous and self-directed learning (technical, personal, professional) materials
- 5.1.4. Use continuous and self-directed learning (technical, personal, professional)

5.2. Lead, support, and collaborate with people

- 5.2.1. Recognize people for their work and service and help them succeed
- 5.2.2. Build high-performance teams
- 5.2.3. Serve as a role model to students
- 5.2.4. Build coalitions and gain support for ideas and projects
- 5.2.5. Work collaboratively to change the culture of STEM

5.3. Act in a globally inclusive manner

- 5.3.1. Communicate effectively across diverse disciplines and communities, including technical communication
- 5.3.2. Listen critically, interact, and work with diverse people and ideas
- 5.3.3. Focus on large problems (grand challenges)
- 5.3.4. Act with purpose

5.4. Work in cooperative/collaborative ways with diverse team members, stakeholders, clients/customers

- 5.4.1. Work in virtual and distributed teams
- 5.4.2. Work in machine-assisted partnerships and teams

6. PERSONAL/PROFESSIONAL ATTRIBUTES

Who you are...

6.1. Value integrity, ethical and moral values

- 6.1.1. Trustworthy
- 6.1.2. Fair and impartial
- 6.1.3. Humble

6.2. Respectful, collaborative, and civically engaged

- 6.2.1. A leader, mentor, and colleague who is open-minded, receptive, and a good listener and team member
- 6.2.2. Empathetic with sense of responsibility and duty to address concerns and issues of diverse people and communities
- 6.2.3. Welcoming and inclusive
- 6.2.4. A clear communicator to various audiences
- 6.2.5. Prudent with resources

6.3. Committed to personal and societal development, well-being, and life-long learning

- 6.3.1. Inquisitive and curious with multiple interests
- 6.3.2. Multi-disciplinary educational background
- 6.3.3. A global, growth mindset with a high aptitude for literacy and awareness
- 6.3.4. Creative, innovative, entrepreneurial, and a risk-taker
- 6.3.5. Resilient and balanced with perseverance, determination, and grit
- 6.3.6. Passionate, confident, and courageous
- 6.3.7. Understand the big picture with an ability to connect various ideas, topics, and interests
- 6.3.8. Commitment to the common good, environmental stewardship, and human dignity

4.5 References

(informing the Competency Taxonomy)

Thank you to all the participants in the FREE workshops who contributed to the Competency Taxonomy, as well as three industry experts interviewed for this project: Dr. Michael Richey, Dr. Lee Hood, and Dr. Michael Fors. Additional literature reviewed is cited below.

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4.6 Second Convening: Pre-Work

Prior to the second convening, beginning on October 21, 2022, the participants were asked to review the FREE-CoT developed from the first convening in May 2022. A narrated slide deck was developed and sent to all participants explaining the model of competencies used to develop the FREE-CoT and how data from the first convening were analyzed and synthesized into the taxonomy. Second, participants were asked to consider how engineering education might have to change to develop these competencies in engineering graduates. Participants were directed to submit three key changes needed in engineering education to better prepare students to become competent future engineers. Three-hundred seventeen (317) key changes were posted on the project's website.

Selection of Participants

The second convening drew 278 applicants, considerably more than the 52 people that applied to participate in the first convening. The larger group represented a wider variety of genders and races (see **Figure 4.10**). They also came from different size institutions representing multiple settings (see **Figure 4.11**) and categories (see **Figure 4.12**). The majority of institutions were public and most offered PhD programs (see **Figure 4.13**). Participants came from all regions of the United States and brought their experience from a wide array of employment sectors (see **Figure 4.14**). The participants brought their extensive insights and experience to inform the project (see **Figure 4.15** and **Figure 4.16**).

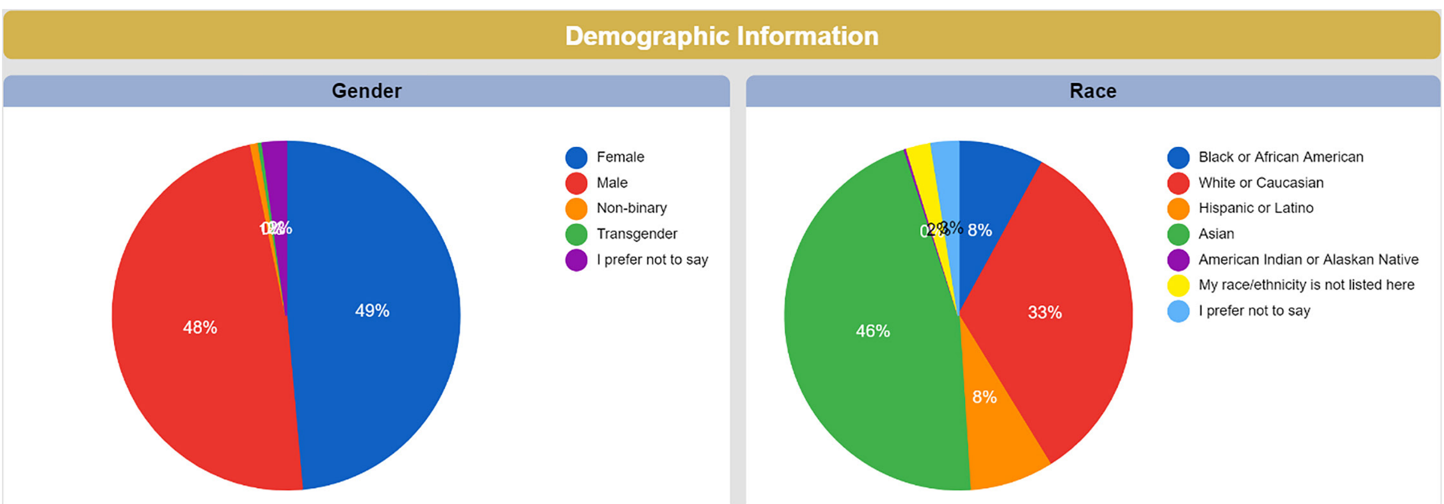

Figure 4.10 Second Convening Participant Demographics

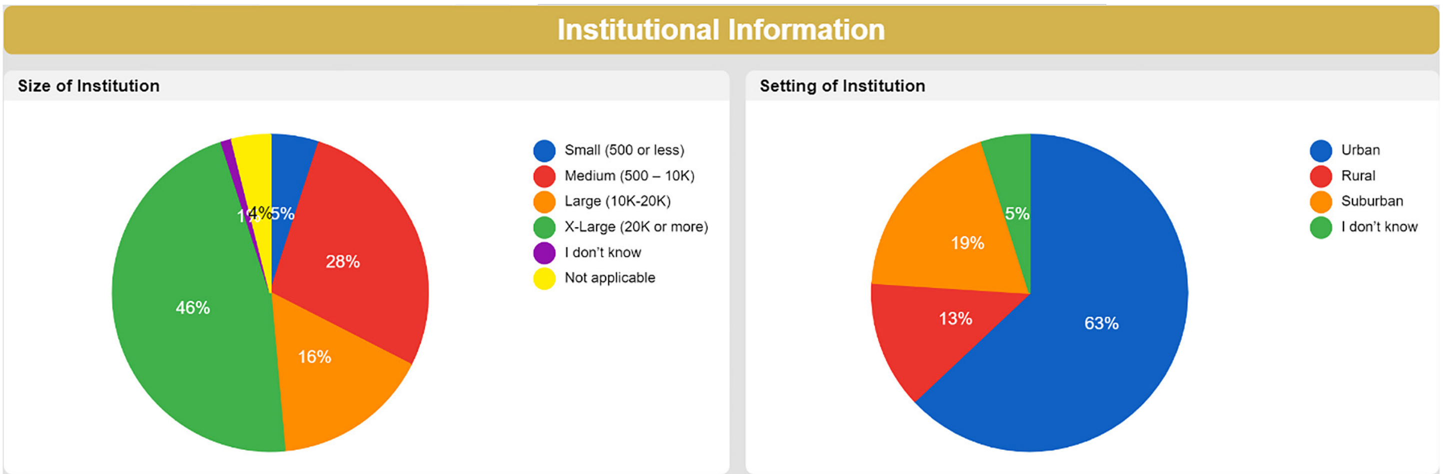

Figure 4.11 Institutional Information for Second Convening Applicants

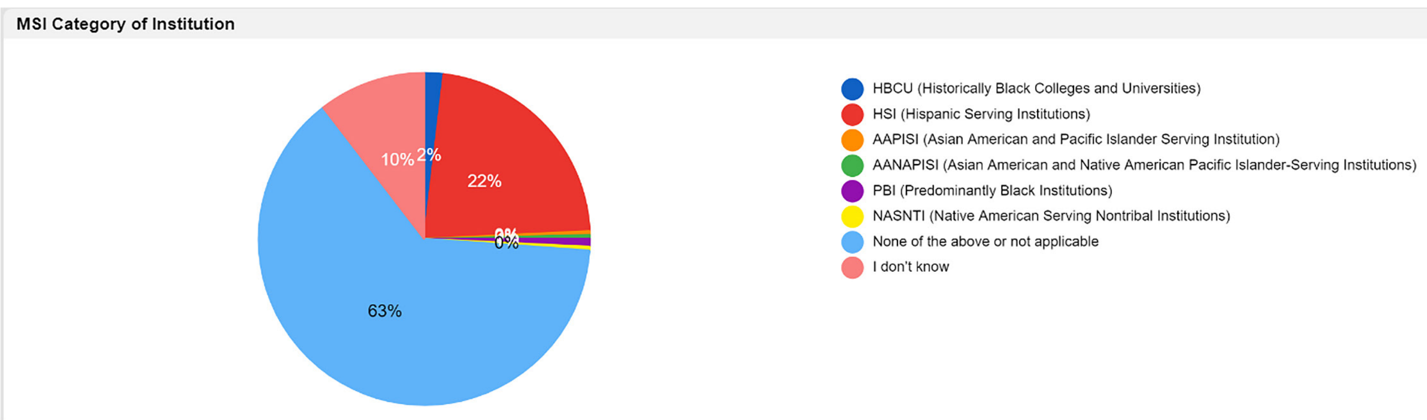

Figure 4.12 MSI Category of Institutions

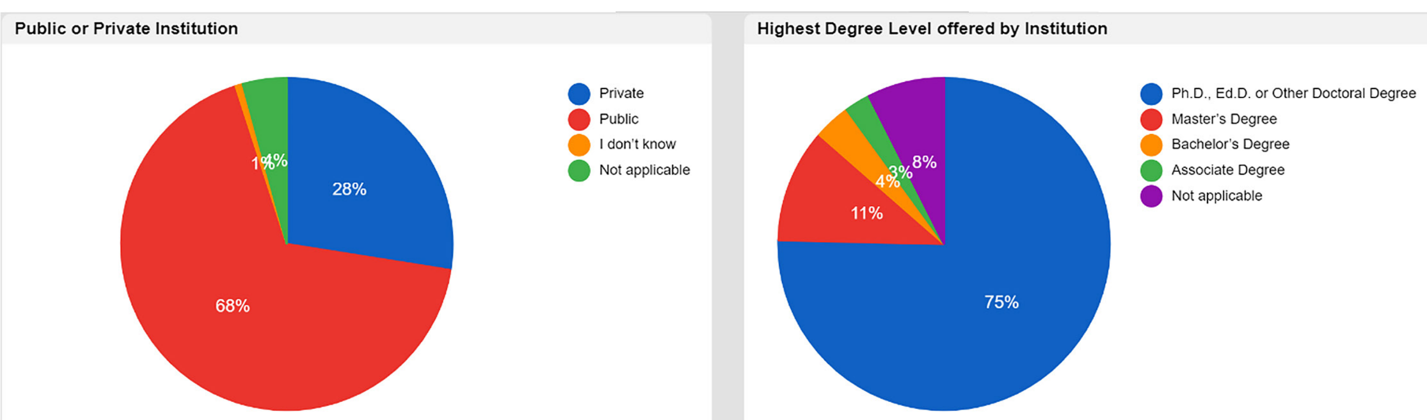

Figure 4.13 Public or Private Institution Status and Highest Degree Offered

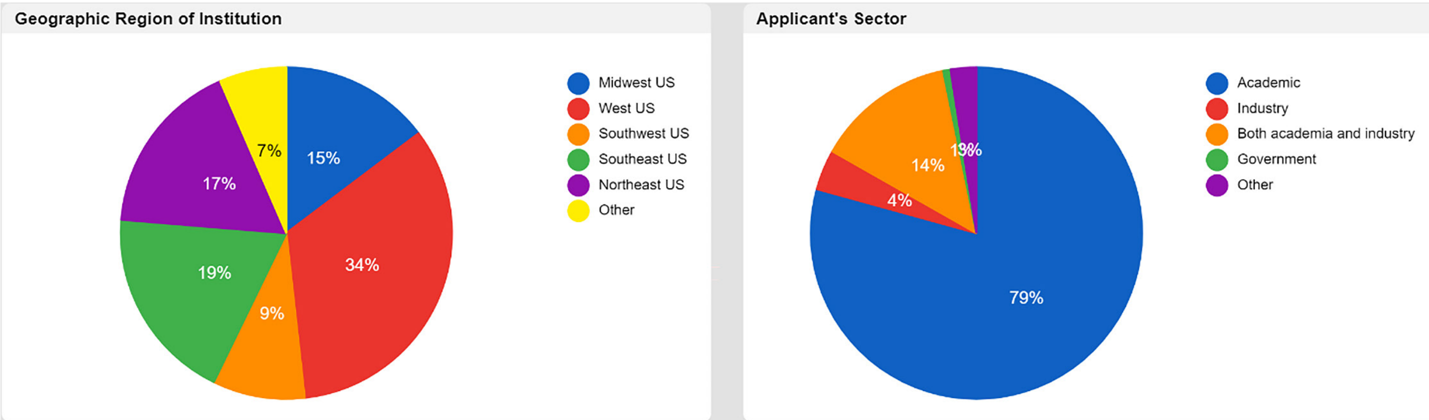

Figure 4.14 Regions Represented by Institutions and Applicant's Sector

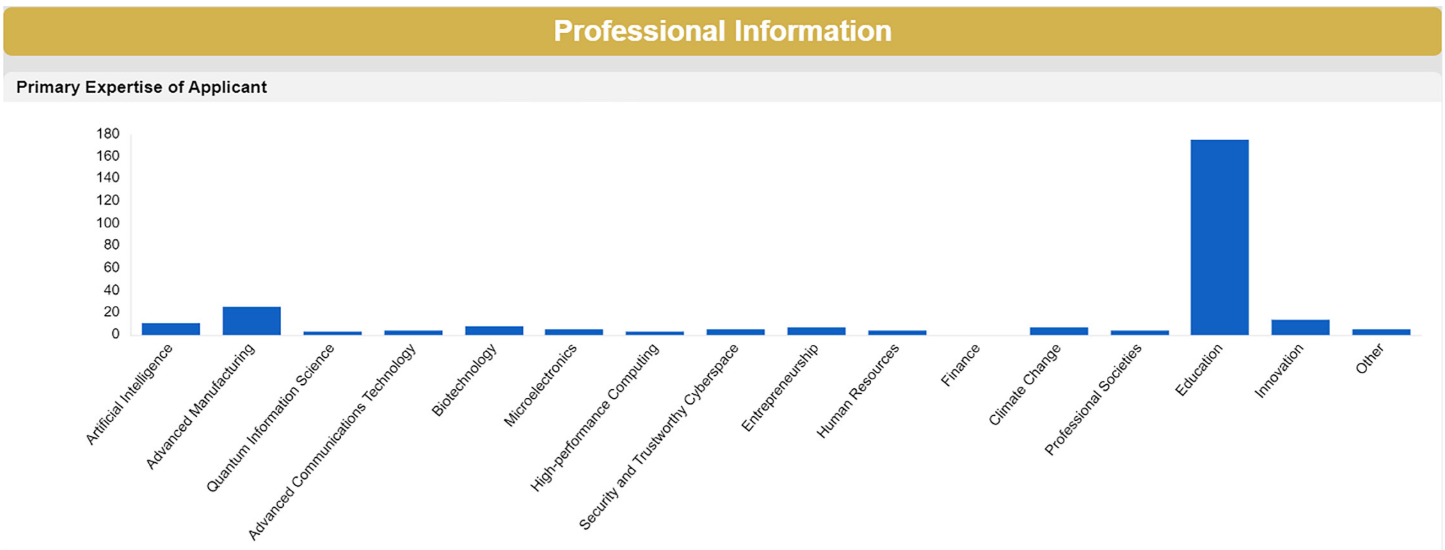

Figure 4.15 Primary Area of Application Expertise

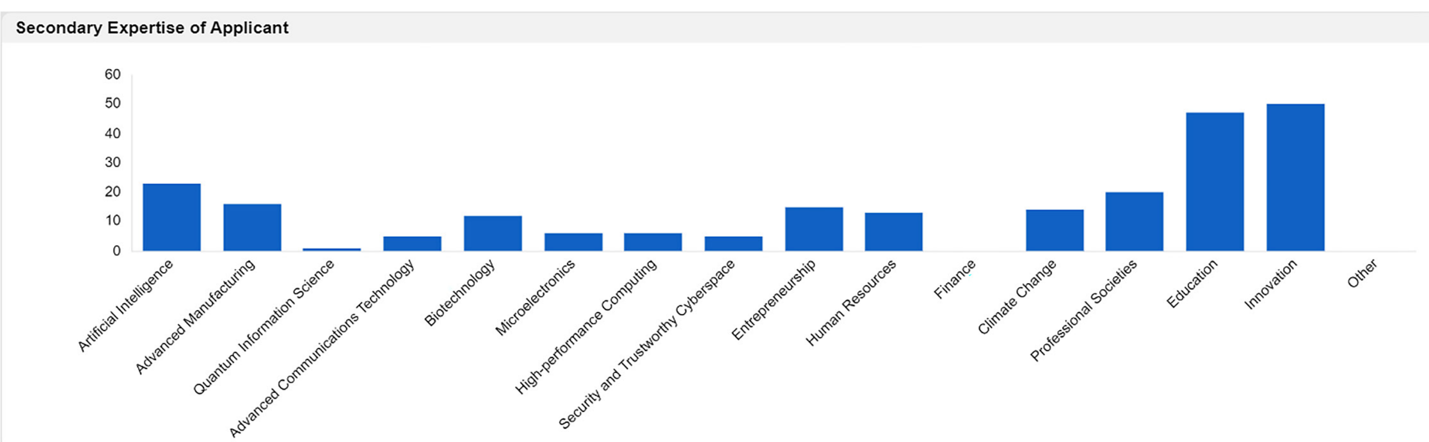

Figure 4.16 Secondary Area of Application Expertise

4.7 Second Convening: Day One (October 21, 2022)

The second convening of this project was held virtually on two consecutive Fridays, October 21 and 28, 2022. Approximately 150 participants joined, representing a diverse range of institutions and engineering fields.

The first day opened with a welcome from the project PI, Dr. Jacqueline El-Sayed. She briefly outlined the plan for the next two days and thanked the participants for joining the project and contributing their talents to this important work. The purpose of this second convening was to operationalize the competencies identified in the first convening held in May 2022 and develop a rubric to guide the implementation of competency-based curricula to better prepare engineering graduates for the future.

Following this welcome, Mr. Toby Scott, the facilitator from Knowinnovation, Inc., further described the planned activities for the two days and encouraged participants to think creatively and come up with novel ideas: "things that haven't been done before." He explained that the first activity was divergent thinking to generate as many ideas as possible. Later we would converge and reduce the list of ideas by selecting the best ones.

Day One - Activity 1: Identify the Implications

There were 22 breakout groups of 5 to 7 participants. The first task was to review the FREE-CoT developed from the first convening's work last spring (see **Table 4.2**). Then, as a group to discuss: What might be the implications of adopting this taxonomy? Participants were asked to consider this question for themselves personally, their students, and their institutions.

A few observations of the groups during this activity picked up bits of their discussions, including:

- Questions about where to focus the action (i.e., undergraduates or graduates)
- Comments about the overwhelming nature of the task (e.g., where do we start?)
- Need to learn new ways to assess students
- Need to upskill faculty
- How to embed the taxonomy into the curriculum
- Need to breakdown academic silos
- Need to go beyond the current (financial) model of higher education

A total of 456 responses were posted. A random sampling of responses included:

- Adopting the taxonomy puts into words our collective goals for student development, something that has often been nebulous or left to those on the margins (such as career development professionals) to figure out.
- Could have very real and positive implications on diversifying the field of engineering.
- Concern over adding additional competencies into an already jam-packed engineering curriculum.
- Do we need to keep conventional silos (mechanical, chemical, electrical) in engineering education?
- Underlying much of this taxonomy is that the students have a sense of agency. How can we encourage that, or at least not crush it?
- Many of the items on the taxonomy may be difficult to assess.
- We need to look critically at general education requirements so they can supplement.

Day One - Activity 2: The "Inversion Technique"

The next activity was intended to "stretch" everyone's thinking. Participants in their breakout groups were asked to come up with ideas that would make engineering education worse for students and their institutions—the inverse of what this project was about.

A total of 1,180 responses were posted. A random sampling of responses included:

- No real-world problems, only introduce fake/made-up problems for students to work on individually.
- Teach students that only engineers have the right thought process to solve problems.
- Take any course in any order from any major—create your own path to engineering!
- I do not care about your career opportunities, industry needs, etc.
- Removing all non-technical courses from majors.
- Teach engineering as bootcamp, be proud of suffering and struggle.
- Exclude creativity from assignments, everyone should have the same answers.
- Focus on weeding out rather than supporting and building up students.
- Require such a heavy course load that there's limited or no time to enjoy the college/ university experience.
- Life is all about work.
- Do absolutely nothing, the system is fine as-is.
- Use student happiness as a metric for teaching quality.

Day One - Activity 3: Operationalize

The third activity of the day asked participants how they would operationalize the taxonomy.

A total of 803 responses were posted. A random sampling of responses included:

- Create pods of teachers and industry representatives who are responsible for teaching various content, so you have someone trained in teaching and learning who supports those from industry coming in to bring valuable expertise and experience.
- Ask faculty how to operationalize the competencies.
- Create examples of low, medium, and high metrics for each competency.
- Have students interview practitioners to determine priority competencies and start with those.
- Allow for failure and iteration in student work, upgrading of corrected work.
- All students would be assigned an industry mentor.
- Field experiences for faculty to stay abreast of industry practices/conditions.
- Synergy between my university and industry in the form of co-developed activities to bring real world in the classroom.
- Engage student organizations.
- Offer structured, guided career coaching and make it a requirement.

Day One - Activity 4: Top 3 Novel & Interesting Ideas

The fourth activity required participants to review and discuss the ideas they posted in the third activity about how to operationalize the taxonomy. Then they were asked to select the three best ideas for further consideration. Participants were asked not to consider only those they thought were feasible, but rather to assume there were no constraints and therefore choose the most novel and interesting ideas. The final list had 67 ideas chosen as the most novel and interesting for operationalizing the taxonomy. We reviewed this list and conducted a simple thematic analysis, combining and synthesizing similar ideas and distilling the list down to 19 ideas (see **Table 4.3**).

Table 4.3 List of Ideas and the Groups Formed to Work on Each Idea

Ideas	Groups
1. How might we create an "engineering ecosystem" for better collaboration among institutions that precede and follow the BS program (including K12, community colleges, and post-graduate programs)?	1A, 1B
2. How might we create student enterprises that are managed and led by students under the umbrella of the university?	2A
3. How might we "blow up" the four-year university degree model?	3A, 3B
4. How might we assess our engineering students without grades and instead through e-portfolios that are evaluated by the workforce?	4A
5. How might we create fine-grained modularized learning experiences, aligned with the competencies, that can be used to create more accessible, agile degree programs?	5A, 5B
6. How might we create new programs as pilot spaces for engineering as a professional degree, as a second entry; particularly leveraging start-up programs?	6A
7. How might we reshape the definition of what an engineer is, what the engineering identity is?	7A, 7B
8. How might we develop a "Record of Competency Growth" that tracks competency development toward achievement of degree-completion standards, using more holistic skills assessment?	8A, 8B
9. How might we transition institutions to a "university-as-a-service" model that enables graduates to return for iterative education experiences in exchange for providing service in other areas?	Idea not addressed*
10. How might we create a taxonomy of faculty development that matches this taxonomy?	10A
11. How might we expose students to community issues, requiring them to solve a problem and communicate with a different group of people (service learning)?	11A, 11B
12. How might we broaden alternative pathways to the completion of an engineering degree?	12A
13. How might we emphasize attributes over knowledge and skills (attributes > skills > knowledge) and build curricula that features attributes over knowledge and skills?	13A
14. How might we implement modular-based curricula focused on project/problem-based learning from day one?	14A
15. How might we change the name of engineering to something like problem-solving and eliminate engineering departments?	15A
16. How might we live, work, and learn together? Groups of students who have diverse backgrounds, cultures, interests, languages, and worldviews living together with "coaches"?	Idea not addressed*
17. How might we create white spaces where faculty, staff, and students can innovate on pedagogy, curriculum, degree programs, etc., without the strictures of tenure, traditional rules, and procedures?	Idea not addressed*
18. How might we value the education of the students, such as in university/program ranking methods or in how higher education evaluates and rewards different faculty contributions?	18A
19. How might we modify as many courses as possible to include interdisciplinary team project work that has students/faculty/others take on a variety of roles over the course of time?	19A, 19B

*Participants were asked to choose the idea they wanted to work on, and three ideas were not chosen (9, 16, 17).

4.8 Second Convening: Day Two (October 28, 2022)

Day Two - Activity 1

From the work done in the previous session one week earlier, the participants were presented with a list of 19 ideas. These resulted from a synthesis of the top three novel ideas identified at the end of Day One's activities. The 19 ideas were presented as a question in the form of, "How might we create … [this idea]? (see **Table 4.3**).

Participants were invited to sign up for which idea they wanted to work on. If the number of participants exceeded seven or eight, the group was divided into two or three subgroups on the idea. Of the 19 ideas provided, 16 were chosen by participants.

Each group was asked how they might operationalize their chosen idea to equip the engineering workforce of the future. The objective was to begin to formulate an action plan, not just a bullet list of tasks. Group members worked from a template that asked them to respond to five questions:

1. This is the idea we want to operationalize… (group members began with one of the stated ideas generated from the previous workshop session and revised, refined, or elaborated it as they wished).
2. Why is it important that your idea is implemented?
3. What do you see yourselves doing within the classroom to make your idea happen (envision an ideal world with no barriers/obstacles, etc.)?
4. What do you see yourselves doing at a program level to make your idea happen?
5. What does success look like if you were able to implement your idea?

Table 4.3 shows the list of ideas generated at the previous workshop session from which individual participants chose one to work on.

Day Two - Activity 2

The final activity of the day was for participants to revisit their work on the different ideas and their group's responses to the five questions. Participants were asked to identify some of the hurdles and barriers they anticipated encountering when trying to implement the actions they described to operationalize the idea. There were various hurdles and barriers identified and these are presented following each summary.

4.9 Post-Work: Creating a Rubric to Guide Change

After the workshop, the participants were asked to provide information useful for creating a rubric to guide changes toward competency-based education. This information was collected via email. The questionnaire asked for the following:

1. Name, email
2. Which idea did you choose?
3. What would be some indicators of high progress toward achieving that idea at the individual, program, and institutional levels?
4. What would be some indicators of moderate progress toward achieving that idea at the individual, program, and institutional levels?
5. What would be some indicators of low progress toward achieving that idea at the individual, program, and institutional levels?
6. How might the indicator(s) need to be modified to evaluate progress in different contexts (e.g., rural, MSI, community college, etc.)? Please specify the context in your response.
7. Please share anything else you think needs to be considered when creating a rubric for the idea you selected. Feel free to use this space to elaborate on your responses above.

Framework and Rubric for Action (v.1)

The Framework and Rubric for Action was developed to inform those assessing progress towards competency-based teaching and learning at the individual, program, and institutional levels based on participants' feedback and comments collected via the post-work questionnaire. There were 76 responses. A simple thematic analysis synthesized the various responses into general themes as the initial indicators (see **Table 4.4**).

Generally, there are two kinds of rubrics in use: 1) general, macro-level items intended to guide organizational change and development, and 2) detailed, usually observable behaviors at a granular level for human resource management and legal compliance in specific settings. The former is the purpose of this rubric. The vast range of fields and applications of engineering requires a comparably broad range of competencies. The indicators in the rubric below are the first version of guidelines for informing program change and development. Further work will be continually needed as different programs in different contexts embark on changes.

Table 4.4 Framework and Rubric for Action

INDIVIDUAL-LEVEL Indicators of HIGH PROGRESS	Moderate Progress	Low Progress
ADMINISTRATORS		
Substantial, high-level support for and actions taken to integrate competency-based educational components in curricula (including policy changes, additional resources, and recognition and rewards for faculty, students, and industry/community partners)		
FACULTY		
Faculty continuously **engage in professional development,** especially related to competency-based education and industry/professional experiences (specific competencies)		
Faculty actively c**ollaborate with each other, community members, and industry partners** to enhance the competency-based learning of students		
Faculty actively participate in competency-based education by **designing competency-based instruction** into their courses (e.g., service learning and project-based learning)		
Faculty provide students with **broad interdisciplinary experiences to enhance competency-based learning**		
Faculty serve as **coaches and mentors to students** emphasizing competency-based development		
Faculty have **real, measurable impact** on student competency development and community/industry engagement		
STUDENTS		
Students have a **high level of support for and participation** in developing their competence		
Students have a **high sense of accomplishment and satisfaction** for competency-based learning		
Students **regularly interact with and serve** community, industry, the profession, and associations		
Students **take greater control of planning and managing their experiences** to meet their goals (individualized pathways)		
Students own, develop, and enhance their **professional identities**		
OTHERS		
Industry and community partners **engage in competency-based programs and contribute** knowledge, projects, mentoring, and advice to students and faculty related to the development of engineering competencies		

PROGRAM-LEVEL Indicators of HIGH PROGRESS	Moderate Progress	Low Progress
Program-wide acceptance and implementation of modular, competence-based instructional approaches and learning outcomes across courses, curricula, and colleges		
Increase **interdisciplinary collaborations** across colleges, industries, and communities		
Offer **customizable, individualized, non-standard degree requirements, program tracks**		
Program **implements and supports robust competency and other professional development**		
Programs **include holistic criteria to assess competency and demonstrate mastery** (including portfolios, presentations, and other alternative measures)		
Programs foster a **broad abundance of resources, mentors, and industry partners engaged** in programs		
Programs focus on **hiring faculty and other professionals having competency-based experience**		
Accreditation efforts **recognize and reward competency-based learning outcomes**		

Table 4.4 Framework and Rubric for Action (continued)

INSTITUTIONAL-LEVEL Indicators of HIGH PROGRESS	Moderate Progress	Low Progress
HIGHER EDUCATION		
Institution shows enthusiastic **commitment and support for competency-based learning** (including from university administration, trustees, etc., as well as students, faculty, community, and industry)		
Institution demonstrates **high level of transparency regarding power** relations in educational change efforts		
Significant **emphasis on, recognition of, and rewards for faculty, staff, and other personnel for development and teaching to advance competency-based education,** including in evaluation, promotion, and tenure process		
Institution has a stronger **emphasis on skills and attributes,** along with knowledge competencies in learning		
Effective increase of **vertical integration of K-16 STEM education**		
Greater emphasis on **real-world issues in education,** including interdisciplinary service learning and project-based learning		
Support for increasing **global faculty exchanges**		
Increased **student enrollments and graduation rates, including increased graduates' success and satisfaction** with engineering education and career		
Competency-based learning outcomes included in **ABET and institution evaluation metrics** (including quality of instruction)		
Complete redesign and integration of programs to **eliminate fixed 4-year/3-credit model in favor of individualized pathways** codesigned by students and faculty		
Competency-based assessment accepted as an alternative assessment instrument, including portfolios and other means of assessing success		
INDUSTRY, COMMUNITY		
Robust **collaboration with industry partners, organizations, and multiple colleges** to integrate competency-based and interdisciplinary education into curricula		
Enhanced **community and industry relations and collaborations**		
Employers support improvements in graduates' competencies for work		

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5.0 Conclusion

These workshops, designed and delivered to define and build the future engineering workforce, concluded with two products useful for preparing engineering students for the future of work. We appreciate the wide range of work in hundreds of different engineering educational programs and by thousands of engineering faculty, instructors, advisors, mentors, managers, and colleagues in education and industry. The products of these workshops are not meant to replace the great work currently found in the engineering ecosystem; however, we believe it is useful to augment and enhance the work of preparing future engineers.

The value of this work—the FREE Competency Taxonomy and Framework and Rubric for Action—are presented as the collective visions and hopes of many engineering ecosystem members that participated in these workshops. We all collaborated over the course of four days, working to create a vision of the future of engineering education that would prepare engineering students to succeed in the future. This is always difficult to predict; however, the holistic and human perspectives incorporated in these competencies and rubric are likely to help guide us for the betterment of society and humanity.

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