Guest Editorial
Special Issue on Using Enquiry- and Design-Based Learning to Spur Epistemological and Identity Development of Engineering Students

THIS Special Issue of the IEEE TRANSACTIONS ON EDUCATION focuses on using enquiry-based design projects to spur engineering students' development, so as to increase understanding and application of the relevant theories, foster higher rates of student development and achieve this in healthy and productive ways.

Each of the eight papers in this Special Issue focuses on a specific aspect, presenting an empirical research study on either epistemological or identity development among engineering students. Five of the papers are on epistemological development or 'epistemic cognition,' and three on identity development. The overall set of resources is presented so engineering educators can gain familiarity with existing theories on how students change and grow over their university years, and can consider the findings of empirical studies and what these might imply for their own teaching and for their students' learning.

I. CALLS FOR CHANGE

"Our house is on fire" argues Greta Thunberg, the 16-year-old environmental activist from Sweden who is successfully shifting public conceptualizations of the natural environment and of climate change where other advocates and scientists had failed to gain traction with the public. Thunberg places the onus on the individual as well as the collective [item 1) in the Appendix]:

"We all have a choice. We can create transformational action that will safeguard the living conditions for future generations. Or we can continue with our business as usual and fail. That is up to you and me."

In the U.K., *The Guardian* newspaper has taken note. On 17 May 2019, their environmental editor, Damian Carrington, explained [item 2) in the Appendix]:

"The Guardian has updated its style guide to introduce terms that more accurately describe the environmental crises facing the world. Instead of 'climate change' the preferred terms are 'climate emergency, crisis or breakdown' and 'global heating' is favored over 'global warming,' although the original terms are not banned.

"We want to ensure that we are being scientifically precise, while also communicating clearly with readers on this very important issue," said the Editor-in-Chief, Katharine Viner. "The phrase 'climate change', for example, sounds rather passive and gentle when what scientists are talking about is a catastrophe for humanity."

"Increasingly, climate scientists and organizations from the UN to the Met Office are changing their terminology, and using stronger language to describe the situation we're in," she said."

This example highlights a shift in conceptions of what is needed to solve complex global challenges. This change, from passive observation of a challenge to active participation in its solution, is needed across society, and indeed across engineering. For *The Guardian*, this represents an alignment of its position as an independent news media organization with the current scientific consensus on the challenge. For engineers, active participation in the solution of global challenges will require conscious awareness of engineers' role in the broader context of global challenges, and the characteristics of engineering practice that enable meaningful participation [item 3) in the Appendix]. Engineers need to expand the ideas they have about being society's leading "problem solvers." They are known for being good problem *namers*, when in fact, they need to become better problem *framers*. Effective engineering practice in today's context requires comfort with complexity, and more conscious and deliberate epistemological and identity development.

Global challenges are complex problems, variously described and ill-structured. They are slippery, difficult to identify, and their edges are difficult to ascertain. Solving them requires iterative approaches [item 4) in the Appendix] and the ability to think strategically while continually factoring in new and emerging data to make informed judgements and decisions [items 5) and 6) in the Appendix].

The education, and the profession, of engineers can benefit from higher agility, greater comfort with uncertainty, and enhanced skill in complex problem solving [item 7) in the Appendix]. Students must learn that framing and re-framing problems is essential to addressing them more fully. They must learn to handle problems at all scales and align responses at multiple scales for greatest affect.

The pressing need for environmental and social justice—in all the many areas that engineers can and do influence—requires an extreme shift away from the status quo. Grand

Digital Object Identifier 10.1109/TE.2019.2923043

challenges, sustainable development goals, and global responsibility must be prioritized. Engineers must be prepared to change the world and must embrace this challenge and this conceptualization of their role in society.

To do this, engineers need to develop a clear sense of purpose, a clear sense of how professional knowledge is integrated and applied, and a clear understanding of the attributes and abilities unique to engineers of various types. They need to think iteratively and holistically. They need more fluid abilities in design as well as the ability to integrate information, research, analysis at many different scales.

II. The Role of Student Development Theory

To assist students in learning such abilities, engineering education—as a global phenomenon—has embraced active- and enquiry-driven pedagogies, such as problem- and/or project-based learning (PBL and/or PjBL), to various extents. Enquiry-based, hands-on learning was core to engineering since the guilds of the 13th and 14th centuries, but as engineering was being introduced into higher education academies at the start of the 19th century, and the professions were coming to be named and regulated, a shift occurred towards theory and away from practical applications [item 8) in the Appendix]. The earlier, shop-based system challenged students to think in context, and see/name/frame problems iteratively in the process of solving them. In universities today, however, engineering students have very few experiences of defining their own engineering problems, and they seldom get to name and rename them iteratively as they seek to pin them down and develop effective responses.

Educators must find more ways to expose students to ill-structured problems and design thinking, and help them develop effective practices for making decisions in highly-complex contexts that integrate a wide range of environmental, social and ethical considerations. They must help students develop effective values, attitudes, skills and behaviors—not just textbook knowledge. They must, in fact, prepare their students to generate new knowledge and brand-new solutions to huge complex problems—not just problems broken down for ease of delivery and assessment.

Cutting-edge education programs have recognized and addressed these issues to some extent, but questions remain over the scalability and potential for mainstreaming such approaches [item 9) in the Appendix]. Until now, there has been much focus on addressing these issues from a graduate-outcomes or program-design perspective. In engineering education today, 'student-centered learning' is almost synonymous with project-based and enquiry-driven learning designs, often with a focus on group- or cohort-level outcomes in isolated units of study. To help students develop in productive ways across their programs of study, engineering education must also draw from student development theory. Theorists in this realm look at the growth and development of individual, and then search for patterns across groups of individuals.

In the United States, theories on how students develop grew out of schools of education, such as the Harvard School of Education where Professor William J. Perry analyzed interview data collected from students over multiple decades and theorized from the results. Perry's seminal theory, a 'schema' describing how students 'develop intellectually and ethically' became the foundation of many other theories now seen to describe epistemic cognition.

This line of enquiry seeks to identify and describe patterns involving students' conceptions of knowledge, how students believe knowledge is made and verified, and how they understand their own ability to make and verify knowledge [item 10) in the Appendix]. Students with sophisticated epistemic cognition consider multiple points of view; they make decisions in context and recognize their own ability to create new solutions and generate new knowledge. Research shows that students who can restructure their thinking to do this get more out of their higher education and are much better prepared for their careers than those who do not [item 10) in the Appendix].

Most of the approaches that use epistemology as an underlying theory to study university students' development assume a basic step model, wherein students arrive at college groomed to be receivers of knowledge—knowledge that is generated and validated outside themselves [items 11) and 12) in the Appendix]. When entering university, most students are just beginning to grapple with multiple perspectives, how to resolve incongruent facts, and ways to reconcile competing points of view. Such skills are necessary for addressing complex and ill-structured problems, yet the typical engineering student progresses less than two positions along Perry's nine-position scheme while earning a Bachelor's degree [item 13) in the Appendix].

Student development theory emerged and expanded from a number of foundational ideas, such as Stanford's [item 14) in the Appendix] call to balance challenge and support, Astin's [item 15) in the Appendix] theory on student involvement that describes a positive correlation between learning gains and a student's level of engagement in rich and productive activities, and Tinto's [item 16) in the Appendix] well-known theories on persistence-to-graduation. These combined with typology theories [items 17) and 18) in the Appendix] can help individuals identify their strengths, and teams balance their approaches. Identity theories [items 19) and 20) in the Appendix], that map the many ways students develop their sense of self and worth, can provide educators with ways of identifying the developmental challenges students face in their journey to become professional engineers.

Although theories on student development are well known among student affairs professionals who provide extra-curricular and auxiliary support to students, they are less frequently known or applied by academic staff. Understanding these theories may aid engineering educators in situating learning for students—helping students develop incrementally, providing effective scaffolding for their development, and providing them an appropriate balance of challenge and support [item 21) in the Appendix].

III. Design Thinking

Transdisciplinary design thinking is core to constructing a sustainable world [item 22) in the Appendix]. Professionals in engineering and related fields cannot continue to produce structures, objects, and responses that fail to consider diverse users, environmental sustainability, social justice and ethics. The good news is that design-, project-, and problem-based learning environments can have significant impact on student learning. Such environments can elicit enthusiastic student engagement in solving complex problems. They can involve real-world contexts so that students see relevance—to themselves and society—and connect new experiences to prior knowledge. When thoughtfully applied, design-, project-, and problem-based pedagogies can promote high-level, holistic development among students.

To help educators understand design thinking and support effective learning, Crismond and Adams [item 23) in the Appendix] conducted a comprehensive review of literature in the process of developing a tool that educators can use in teaching design. This tool holds relevance in engineering education and even science education.

The move from beginning to informed designer is marked by two key elements: (1) attending to the situated aspects of design (e.g., context, human and social systems, subjectivity) and (2) shifting away from approaches appropriate for more well-structured and well-defined problems (means-ends analyses that work well with deductive reasoning problems, for instance) to those that are necessary to deal with the uncertainty and ambiguity of ill-structured and ill-defined problems (e.g., abductive reasoning problems). Overall, the move from beginning to informed designer is a shift in thinking—an informed designer cannot design by simply using approaches for solving well-defined problems.

Engineering educators are in a position to model effective decision-making, demonstrating for students the process of iterative problem-framing in the process of problem-solving, as discussed in this Special Issue by Walker *et al.* Subsequently, in observing how well students navigate their way through complex problems, they can help students who are encountering difficulty by applying theories and using tools like Crismond and Adams' matrix.

For educators, learning to model complex thinking and sophisticated forms of cognition for students, and learning to apply development theories while teaching, can be daunting. Engineering educators themselves can benefit from having others to model effective practices. In addition to reading and studying theories on how to promote student development, teachers also need to learn from others on campus who know how to do this. They need to experience success in, for example, delivering assignments, tutoring students, modeling effective processes and decision-making for students. Teachers can help each other learn how to facilitate students' ownership of problem-framing, as they work up from small problems to large-scale, complex, and trans-disciplinary problems.

To learn such education-delivery techniques and skills, engineering teachers can band together and take a project-based approach themselves, working together and consulting each other as they incrementally shift the way they facilitate leaning in specific content areas [item 25) in the Appendix]. Co-teaching with others, particularly those with other ways of teaching, framing problems, and conceptualizing the world, can help. In this Special Issue, Ozkan *et al.* describe one such scenario, where teachers and students from three significantly different disciplinary perspectives learn together, and begin to identity and reconcile assumptions embedded in their fields that can limit vision by filtering out too much of what they might otherwise see. Disciplinary schemas can be helpful for facilitating quick problem-solving, but being able to understand and tap into ways of thinking and doing within other fields is necessary for holistically addressing problems in today's world.

IV. An Introduction to the Papers on Identity

The first set of papers in this issue deals with identity development and the potential of enquiry- and design-based learning to support it. Seminal work in the realm of understanding and describing identity development among third-level students was done by Chickering [item 26) in the Appendix], and further developed and refined by Chickering and Reisser in *Education and Identity* [item 27) in the Appendix].

Regardless of their specific realm, identity development theories share common elements, wherein the individual moves from: (1) unexamined identity, to (2) conformity, then to (3) resistance and separation, and finally to (4) integration. Identity theories hold relevance for engineering education; they have implications for supporting diversity and helping all students feel a sense of inclusion and belonging. They are also useful for helping student engineers first recognize, and then shape, their professional purpose in society. For a student to identify as a problem-framer, or a person who can solve complex global challenges and improve environmental sustainability and social justice via work as an engineer, could be an important step forward.

In this issue, three papers explore the formation of professional identity, to serve as an introduction to the application of identity theory in engineering education. They look at specific student populations: (1) early-career electrical and computer engineering students, (2) Latinx engineering students, and (3) graduate engineering students.

In "Design Experiences, Identity, and Belonging in Early-Career Electrical and Computer Engineering Students," authors Jacqueline Rohde, Lisa Musselman, Dina Verdín, Allison Godwin, Brianna Benedict, Adam Kirn and Geoff Potvin found that design experiences can foster engineering identity and belonging, and that students interpreted these constructs differently. Student descriptions of identifying as engineers centered on how well they performed on authentic engineering tasks and how interesting they found such activities. When explaining their sense of belonging in engineering, students framed the discussion by comparing themselves to peers. The authors aim to help educators foster a healthy sense of identity and belonging among students in engineering and, ultimately, enhance persistence rates.

The paper "Factors Influencing Engineering Identity Development of Latinx Students," by Meagan Kendall, Maya Denton, Nathan Choe, Luis Procter and Maura Borrego, reports a mixed-methods study that included an online survey complemented by ten interviews with Latinx students at two different universities in Texas. Three student characteristics predicted 5.9% of the variance in engineering identity; these were attending a Hispanic-Serving Institution, having a parent holding an engineering degree, and gender. Six affective factors explained an additional 28.1% of the variance. These were: engineering interest, engineering recognition, engineering performance/competence, analysis, framing and solving problems, and tinkering. The authors seek to understand student persistence so as to support persistence among Latinx engineers.

Authors Nathan Choe and Maura Borrego focus on engineering graduate students in their paper "Prediction of Engineering Identity in Engineering Graduate Students." The authors used a multi-scale survey instrument to identify, through factor analysis, four significant and positive predictors of graduate students' engineering identity: (1) engineering interest, (2) engineering recognition, (3) engineering competence, and (4) interpersonal skill competence. Their final model, created using multiple regression techniques, uses these four factors along with student characteristics; it predicts 60% of the overall variance in engineering identity. The findings are important because this model predicts substantially more than existing models for undergraduate engineering identity. The authors explain that the study "lays the groundwork for future investigations and interventions to foster engineering graduate students' engineering identities and retention."

Together, these papers provide guidance on how engineering identity can be examined, and formed through education, to create a more comprehensive picture of students' path to the profession and the hurdles and opportunities along that path. The Guest Editors believe that with understanding of how students develop identity, engineering educators can more consciously inform the sense of purpose students develop in university, and help students direct their engineering efforts toward worthy environmental and social causes. These papers on identity help support specific, diverse student groups, and thus promote social justice across the profession of engineering.

V. An Introduction to the Papers on Epistemology

The second group of papers in this issue focuses on epistemic cognition. Providing an excellent introduction to Perry's theory as applied to engineering education and research, Jiabin Zhu, Rongrong Liu, Qunqun Liu and Zhinan Zhang have explored "Engineering Students' Epistemological Thinking in the Context of Project-Based Learning." This team built on their prior work developing an instrument, based on William Perry's schema [item 10) in the Appendix], to quantitatively assess student development. Interviews were conducted with engineering students to identify demonstrations of students' relativistic thinking in project-based learning (PBL) activities, and factors connected to students' relativistic thinking. The researchers identified instances of sophisticated epistemological thinking in students' descriptions of: their broadened thinking, solving problems within constraints, conducting feasibility analyses, integrating commercial considerations, connecting theory with practice, and the like. Epistemological development, the authors assert, was supported by guidance from professors, collaborations with peers, communications with various stakeholders, and dealing with contextually complex and open-ended projects.

In another article, Christopher Rennick, Carol Hulls, and Kenneth McKay explored ways to help first-year engineering students move beyond a dualistic worldview, through multiplicity, and into relativism within the specific domain of software design. Their article describes "Introductory Engineering Decision-Making: Guiding First-Year Students to Relativism in Software Design." They assessed outcome of their intervention using a mixed-methods (survey plus interview) approach that integrated Perry's framework [item 10) in the Appendix]. The instructors built a semester-long course to teach procedural programming, software design and open-ended, contextualized problem-solving. They implemented coaching methods to help deter students from retreating to the lower positions of the schema as students can tend to do when they feel overwhelmed. "By end of term, most students were comfortable with the concept that there were multiple ways to approach a programming problem and that there were many reasonable solutions, depending on the context and the assumptions made," the authors state, indicating that students were approaching Relativism as defined by Perry.

In the context of senior capstone, Erica Walker, Matthew Boyer, and Lisa Benson explored "Using Studio Design to Support Cognitive Apprenticeship and Epistemic Change in the Engineering Classroom." Interview data, video footage of classroom interactions, and reflections written by students were analyzed thematically. Analyses suggested that cognitive apprenticeship methods applied in a design studio environment had a positive effect on epistemic and cognitive growth for engineering students. The cognitive apprenticeship theory encourages teachers to identify and make explicit, through open dialogue and questioning (by all participants in a classroom) otherwise tactic aspects of the curriculum. This helps counteract the tendency for experts to leave many of their field's underlying assumptions unstated. The paper's authors explain, "The sociological aspects of the Cognitive Apprenticeship framework show that learning, feedback, and reflection should move freely in both directions between instructors and students." In the study, students developed "epistemic frames including a stronger understanding of themselves and increased confidence in their ability to communicate and approach problems within the context of their chosen profession."

Jonte Bernhard, Anna-Karin Carstensen, Jacob Davidsen and Thomas Ryberg also investigated students' cognitive and epistemological development in advanced design studios. These scholars focused on epistemologies students used in situated action and the students' development of epistemic fluency. Their paper, "Practical Epistemic Cognition in a Design Project—Engineering Students Developing Epistemic Fluency," reports qualitative analysis of video of upper-year architecture students working together. The authors' novel methods integrated ethnographic analysis, conversation analysis, and embodied interaction analysis. Studying 'epistemologies in action' these researchers found that students employed models, drawing, diagrams, physical gestures, words, notes and the like as epistemic tools to build understanding of a design under development. Students also used a wide array of resources to develop shared understanding and produce new design solutions as a team. Advanced design students tended to do this seamlessly, reflecting what the authors call 'epistemic fluency.'

Like students, educators can also benefit from developing epistemic fluency. The paper "Teacher Learner, Learner Teacher: Parallels and Dissonance in an Interdisciplinary Design Education Minor" by Desen Ozkan, Lisa McNair and Diana Bairaktarova explains that trans- and interdisciplinary design curricula challenge engineering teachers and students alike. The paper provides a valuable introduction to the Reflective Judgment Model created by King and Kitchener [item 28) in the Appendix] as well as conceptualization of campus learning environments posited by Strange and Banning [item 29) in the Appendix]. The authors drew parallels between the challenges and learning experienced by teaching teams and student teams in one interdisciplinary certificate program, collecting data via interviews, classroom observations, and students' written reflections in three courses. Like the students enrolled in their modules, the teachers also had to negotiate to construct shared understandings of complex contexts. Teachers and students alike addressed disciplinary assumptions and tacit values as they learned to work across fields. Discomfort with uncertainty emerged as a prevalent theme.

Taken together, these papers point to ways of shifting the perceptions held by students and educators of what engineers do and the responsibilities they bear. Understanding these theories and using them to support classroom activities can help educators support holistic development of students—considering head, heart, hands and health—and foster the abilities that engineering professionals need to design and construct effective and globally responsible solutions to today's array of needs and challenges.

Acknowledgment

Thanks go to the many authors, identified above, involved in producing this Special Issue. They have extended this realm of inquiry in engineering education by conducting and reporting their empirical analyses of data collected on three different continents. Thanks, however, cannot stop there, as dozens of other people supported the work of these authors. The peer reviews and guest editors—representing four different continents—gave countless hours to enhancing the quality and value of the issue. Peer reviewers were: Folashade Akinmolayan, John Bachman, Yifat Ben-David Kolikant, Rebecca Broadbent, Shane Brown, Thomas Cosgrove, Scott Daniel, Inês Direito, Mathew Docherty, Kenneth Faller, Robin Fowler, Kimberly Freeman, Allison Goodwin, Ashley Grifin, Barrett Hazeltine, Sally Male, Robert McQuade, Dan Moore, Stuart Palme, Juliana Prpic, Kenneth Reid, Raul Rengel, Monique Ross, Noah Salzman, Iain Skinner, Jessica Swenson and Esther Ventura-Medina.

The following guest editors helped Shannon Chance, Associate Editor of IEEE Transactions on Education, guide the character of the overall collection: Bill Williams, Tom Goldfinch, Robin Adams and Lorraine Fleming. Thanks go to these scholars for persistent contributions of time and effort made over the 18 months while this issue has been under development. Shannon Chance's work on this Special Issue was supported financially by the European Union via a Marie Sklodowska-Curie Actions (MSCA) fellowship provided to Shannon Chance for a larger project titled, "Designing Engineers: Harnessing the Power of Design Projects to Spur Cognitive and Epistemological Development of STEM Students" (Call identifier: H2020-MSCA-IF-2016, Project 747069, Project acronym: DesignEng).

The issue also benefits from quality leadership provided by former Editor-in-Chief Jeff Froyd, current Editor-in-Chief John Mitchell, and Editorial Administrator Kirsty Mills.

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Appendix
Related Work

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