What is scientific knowledge? Engaging Polanyi's epistemology in engineering ethics

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Abstract

Although epistemology is not typically addressed in discussions of ethics at an undergraduate engineering level, assumptions about the nature of knowledge play an important role in ethics. This role may be highlighted in the epistemic values operating in ethics case studies, or in analysis of the relation between technology and society. For example, some critics of the place of technology in society argue that western society's misconceptions of truth and knowledge undermine the possibility of effectively critiquing technology's role in society. Examining implicit epistemologies is thus a valuable step towards developing a deeper ethical engagement. However, philosophical treatment of epistemology can be daunting and appear irrelevant for engineering students. This paper reports on an epistemology discussion unit in a 2-credit engineering ethics course required for all undergraduate engineering students at Dunwoody College of Technology. As part of a sequence of units on technology and society, the goal is to introduce undergraduate engineering students to epistemological assumptions and discuss the impact of these assumptions. Given the context of an engineering ethics course, no philosophy background is assumed for students, and activities avoid philosophical terms where possible. The discussion-based class activities are designed to explore the emphasis on objective knowledge in common conceptions of "scientific knowledge," and the limitations of this popular conception of knowledge. Michael Polanyi's description of tacit knowledge is used to examine the importance of non-explicit and non-objective knowledge in the sciences and in everyday activities. Class activities also explore the role of focal and subsidiary awareness, as well as the role of authority in learning. Polanyi gives a nuanced account of the non-explicit aspects of knowing that provide a correction to naïve realism, while still holding to a realist ontology. Student feedback has affirmed student engagement with the topic and ability to grasp the concepts. Ongoing work aims at improving long-term retention by increasing the connections between this unit and other course activities.

Introduction

Engineering ethics textbooks typically do not include a discussion of epistemology, or only a brief mention as in Whitbeck [1], who includes epistemic values in a discussion of value judgments. As Whitbeck notes, epistemological assumptions play an important role in assessing what kind of knowledge is valid for consideration in an ethical problem. Does knowledge consist of only objective facts? Is knowing primarily a matter of sorting out correct answers from the incorrect?

Although not typically given direct treatment in the context of an engineering ethics course, many educational research studies have considered the personal or implicit epistemologies of students. Student assumptions about the nature of knowledge and knowing have a bearing on their ethical reasoning and development, as well as their ability to effectively tackle complex problems in an engineering design or professional context.

Discussions of the epistemology of college students often begin with reference to the work of William Perry [2]. Building on the framework of Jean Piaget and developmental psychology, Perry described epistemic changes in college students as an ordered sequence of stages of development. Students entering college were characterized by early stages, in which they view knowledge as simple, certain, binary (right or wrong), and residing with authorities, who are the source of right answers. As students engage with the pluralistic college context, they progress to higher stages of the scheme, in which they perceive knowledge and values as contextual and relative. In the highest stages, students orient themselves by personal commitment in this relativistic context. Perry's scheme describes epistemological and moral development as inseparable, where changes in moral reasoning are the result of changing assumptions about knowledge, truth, and authority.

Like Perry's influential scheme, most subsequent proposals for personal epistemology are models of a patterned sequence of development (e.g. [3, 4]). In contrast, Schommer's proposal [5] understood personal epistemology as being composed of multiple independent dimensions or independent beliefs about knowledge. The questionnaire developed by Schommer for assessing epistemological beliefs has been widely used for quantitative studies, both directly (e.g. [6]) and with modification (e.g. [7]). Reviews of this work [8, 9] question the validity of the instrument for establishing the independence of Schommer's dimension, and the inclusion of beliefs about intelligence (Schommer's "innate ability" dimension) and speed of learning ("quick learning" dimension) in an epistemology model. In reviewing proposed models, Hofer and Pintrich [8, 10] argued that, correctly defined, personal epistemologies consist of beliefs about the nature of knowledge (*certainty of knowledge*, ranging from fixed to more fluid or changing, and *simplicity of knowledge*, ranging from a collection of facts to complex interrelated concepts) and the nature of knowing (*source of knowledge*, as residing with an external authority or with the self as a maker of meaning, and *justification of knowledge*, which can rely on authorities or reasoning and evidence).

Studies of engineering students have used these development models to show progression along Perry's scheme [11, 12], in particular through courses that involve open-ended discussion and design addressing complex and ill-formed problems [11]. But studies on engineering students have also observed differences in personal epistemology from students in other disciplines. When comparing students in engineering to those in the arts, humanities, and social sciences, Jehng, et al. [7] found that engineering students were more likely to view knowledge as certain, with its source in authorities, and acquired in an orderly process. Like Jehng, et al., Paulsen and Wells [6] used the framework of Schommer [5], and found that engineering students were significantly more likely to view knowledge as simple and certain. Following Biglan [13], they suggest this is because the "hard field" of engineering (in contrast to "soft fields" such as the humanities) is dominated by a single paradigm that specifies content and methodology for the field. Cruz, et al. [14] investigated the implicit epistemology of undergraduate students in a transdisciplinary art, media, and engineering program. The authors identified constructionist epistemological alignment when students spoke of the artistic themes of their work. However, when speaking of engineering aspects, positivist approaches dominated, with strong right/wrong binaries and reference to correct method.

Studies of engineering faculty have also noted positivist characteristics, such as a preference for objective data and quantitative methods over qualitative [15, 16]. In a study of civil engineering faculty, Montfort et al. [17] report participants expressed a strong conviction of knowledge corresponding to an external reality, and the possibility of proving objective truth. However, many participants also understood their own knowledge as limited and context-bound, which the authors argue demonstrates personal epistemologies that are more complex than just a modification of positivism into postpositivism. The authors also noted that participants made a sharp distinction between research, where complex reality exposes the limitations of knowledge, and fundamental engineering courses, where problems are simplified to remove all ambiguity.

Where epistemological positions are mentioned in the above research, the frequently cited paradigms of Guba and Lincoln [18] are used (as in [17]) or similar limited set (as in [14]). Many of the authors operate from constructivist paradigms, as stated explicitly (e.g. [14, 18]) or evident from the methods and conclusions (e.g. [6]). Commitment to realism in participants is taken as an indication of positivist or postpositivist epistemology. The use of postpositivism as a catch-all category for any non-positivist realist epistemology represents a significant limitation, as acknowledged by Cruz, et al. [14].

The literature reviewed above demonstrates the importance of personal epistemologies to learning, in both ethics and engineering. Several of the authors discuss the epistemic motivation for their pedagogical approach. However, direct discussion of epistemology is largely absent in ethics courses taught outside of the context of formal philosophy. This work describes explicit attention given to epistemology in the context of an engineering ethics class, drawing on the work of Michael Polanyi. As discussed below, Polanyi provided an important early critique of positivism, and his concepts of tacit and personal knowledge have proved of enduring value in a diverse range of diciplines.

Course background and objectives

The class activities discussed below were developed as part of the ENGR4110 Engineering Ethics, a 2-credit course required for all undergraduate engineering majors at Dunwoody College of Technology. This course is central to our strategy for addressing internal program goals and ABET accreditation outcomes for student ethical development and reflection. The Engineering Ethics course is designed as an interactive discussion class, with in-person attendance and small class size (< 20 students). For the last six course offerings, explicit attention to epistemology has also been included as described below.

Learning outcomes for the Engineering Ethics course emphasize personal ethical engagement in engineering. Students completing the course should have an understanding of engineering as a moral activity, and have a starting point for ethical framework that can guide conduct as a practicing engineer. Student-facilitated discussions of ethics case studies are used to encourage reflection on issues of engineering professional ethics. Students are also encouraged to connect ethical reflection with their own values and experience, culminating in a personal code of ethics assignment. In this context, discussion of epistemology is intended to clarify the role of epistemic values and presuppositions in personal ethical reflection as well as in the complex ethical situations of the historical case studies.

The class also addresses broader questions regarding the relationship between technology and society, which constitute a second emphasis of the course learning outcomes. Students completing the course should be able to identify prevailing cultural attitudes toward technology, and assess how technology and its cultural interpretations affect society. Students study and debate the question of technological determinism: is technology merely a tool used whose effect depends on the intent of the user, or does the nature of the technology determine its social effects? The final summative assignment is a research project, for which most students choose a topic related to the relationship of technology and society. Epistemological arguments are important to many critiques of technology and society, so an understanding of epistemology can provide a valuable background for class readings and discussion.

A final course learning objective directly addresses the discussion format of the class: students should be able to "communicate respectfully, demonstrating active listening and thoughtful engagement with the complex issues involved." This type of engagement is an important skill for dealing with problems that are more complex and open-ended than those students typically encounter in core engineering classes. Discussion is built into every class session, with a variety of large and small group discussion structures. Thoughtful engagement with unfamiliar perspectives is often impeded by limited epistemic values: what is allowed as a valid fact and what is dismissed as subjective. Examining the place of tacit knowledge against the background of limited common epistemic values is intended to provide a basis for an appreciation of other forms of knowledge. A widened view of knowledge can also broaden the appreciation for diverse perspectives in ethical discussions.

Polanyi's epistemology

The class discussion on epistemology draws on the ideas of Michael Polanyi (1891-1976), as presented in *Personal Knowledge* [19] and *The Tacit Dimension* [20]. During his early career as a physical chemist, Polanyi made important contributions to chemical kinetics, x-ray diffraction, and gas adsorption. As he shifted attention to the philosophy of science later in his career, Polanyi was an important critic of logical positivism. Where positivism emphasized explicit, articulated, formal knowledge, Polanyi's account of the social construction of science drew attention to tacit, unarticulated, and nonformalized knowledge [20, 21]. Polanyi is perhaps best known for this concept of *tacit* knowledge, which is knowledge that is difficult to articulate, and which Polanyi used to account for much of human knowing, include language and skillful bodily performance.

Polanyi shows how tacit knowledge is also essential in scientific research; essential to what is perhaps the most important activity of science: the researcher pursuing discovery by seeing a problem. With just formal, explicit knowledge, the search for a problem is an absurdity. As Plato pointed out in Meno's paradox, either you know what you are looking for, and there is no problem; or you do not know what you are looking for, and then you cannot expect to find anything. In contrast to explicit knowledge, "Tacit knowing is shown to account for a valid knowledge of the problem, for the scientist's capacity to pursue it, guided by his sense of approaching its solution, and for a valid anticipation of the yet indeterminate implications of the discovery arrived at in the end" [20, p. 24]. This kind of knowing is not formal or objective, but is personal and involves deep commitment to the conviction that there is something to be discovered.

Although not emphasized in the activities below, personal commitment is an important aspect of Polanyi's epistemology. Polanyi argues that an epistemic act cannot be justified by rules or evidence alone, but requires a personal act of affirmation that relies on tacit as well as explicit knowledge. *Personal knowledge* is the unification of these subjective and objective aspects of knowing, and provides a foundation for a realist epistemology [19]. Incidentally, here Polanyi's work provides the basis for Perry's later stages: "Polanyi's analysis considers precisely what our students address: the ultimate welding of epistemological and moral issues in the act of Commitment" [2, p. 226]. But for Polanyi, commitment is truth-directed rather than coherence-directed, and so presupposes ontological realism.

A commitment to realism underlies all of Polanyi's work [22, p. 10]. This is in contrast to the constructivism that is influential in education theory and which tends toward anti-realism [23]. (As von Glasersfeld [24] explains, constructivists typically do not deny the existence of the external world, but rather our ability to rationally know a reality beyond experience.) In engineering fields, where many practitioners consider a commitment to realism essential [17], the educational implications of abandoning realism are significant [23]. Although there are various other realist alternatives to positivism, none has emerged as a clear favorite in science [25]. In this context, Polanyi's work provides an epistemology that avoids the naïve realism of positivism, but maintains the ontological realism many consider necessary for engineering education. Polanyi's account of knowing has also received a positive reception in diverse fields outside of science [21].

Class activities

The classroom activities described below were developed to explore implicit epistemological assumptions and discuss some of their limitations. These activities include discussions of scientific knowledge, tacit knowledge, and the role of experts or authority in knowing. These discussion activities were conducted during the second half of semester, and filled the single 2-hour weekly class period.

- **Perceptions of scientific knowledge:** In this activity, students explain their perception of valid knowledge in the domain of science and engineering. Through a class discussion, these characteristics of valid knowledge are mapped out on the board around the title "scientific knowledge," with results like those shown in Fig. 1. In addition to positive descriptors (e.g., "repeatable" and "based on evidence"), descriptions of the opposite are also noted (e.g., "biased" and "superstition"). This discussion typically involves clarifying the definition of key words such as *subjective* or *objective*. After students have finished the brainstorming activity, the result is often much in line with Polanyi's characterization of positivist epistemology: "scientific rationalism only allows explicit statements based on

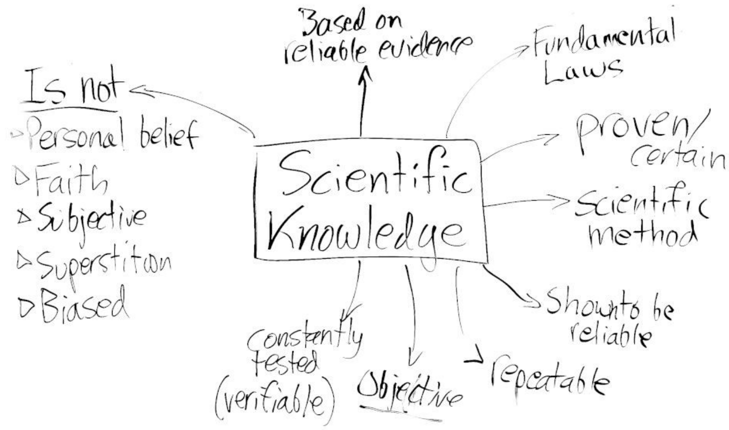

Figure 1: Descriptions of scientific knowledge suggested by students during an in-class activity directed at defining the term.

tangible data, derived by formal inference and open to repeated testing" [20, p. 20]. As noted above, although positivism has since been discredited as an epistemological theory [26], positivist assumptions remain commonplace in popular perceptions of science.

- **Tacit knowledge:** Polanyi [20, 19] uses several simple, everyday examples to illustrate that "we know more than we can tell" and to introduce tacit knowledge. In this activity, students are asked to look for a face they recognize while shown a series of slides with multiple portrait photos on each slide. After several slides with unknown faces, students identify the face of a well-known faculty member. With the images removed, students are then asked to describe the known face and how they were able to identify it. This discussion illustrates that although we can describe many facial features, human facial recognition relies on tacit knowledge, which can only partially be made explicit. The same idea is then illustrated by the discussion of skills that involve bodily movement, such as sports or riding a bicycle. In any skillful activity, our focus is on the outcome or performance, and we are only tacitly aware of what is going on with our bodily movements. As mentioned above, Polanyi used the concept of tacit knowledge to demonstrate the importance of non-objective and non-explicit knowledge, not just for everyday life but also for science.
- **Magic Eye pictures:** In this activity, students are each given a Magic Eye picture, which is an autostereogram, a computer-generated image of repeated patterns that hides a 3D picture. As students follow the directions to focus beyond the page, most are able to see the 3D image. This enjoyable activity illustrates the epistemic process of changing focus from the *subsidiary* particulars to *focal* awareness of the integrated picture [27]. By analogy, this activity can also illustrate epistemic insight, or the 'aha' moment, in which a more effective understanding is achieved by cognitive restructuring. Polanyi [20] describes this as a process of *integration*, in which we attend *from* the observed particulars *to* the coherent entity that they compose.
- **The role of authority:** This discussion explores the role of authority, such as textbooks or instructors, in scientific knowledge. Students are asked to recall their learning of an

important theoretical concept in their discipline, such as the laws of thermodynamics for mechanical engineering. The previous brainstorming activity for scientific knowledge typically brings out the role of a scientific method and the importance of refutability or testability. Yet for a student, important laws and theorems are typically assumed on authority, rather than re-derived. Authority thus plays an important role in learning science or engineering, where a degree of trust in the teacher is necessary to learning the basics of the theory. But after reaching competence in the discipline, a continued over-reliance on authority may be a avoidance of the responsibility of a committed knower. Polanyi [19, 20] has pointed out this tension in the history of science, where revolt against authority played an important role, but belief and trust are essential to learning.

The above activities help illustrate important aspects of Polanyi's epistemology with examples from science and everyday experience. Connections are made to other parts of the course in which these epistemological concepts emerge. Several examples are provided below. These connections are discussed during the above activities, as well as in other class units, both before and after the epistemology unit.

- **Technical experts** often play an important role in questions of technology and society. How should these authorities be weighed against other voices in ethical deliberation? Many insightful critics of the role of technology in society emphasize the legitimizing role of implicit positivist epistemologies. For example, Theodore Roszak [28] characterized a technocracy as "that society in which those who govern justify themselves by appeal to technical experts who, in turn, justify themselves by appeal to scientific forms of knowledge. And beyond the authority of science, there is no appeal." Here, Roszak echos the earlier analysis of Jacques Ellul [29], who attributed the "authoritarian" power of the technological system to the authority of technical experts who rely on quantified numerical data: "only that is knowable which is expressed... in numbers. To get away from the so-called 'arbitrary and subjective,' ...the scientist must get back to numbers" [29, p. 18]. A basic understanding of the limitations of positivism can help students better appreciate the significance of these limitations on epistemic values.
- **Ethics case studies** can also illustrate epistemic values in the professional engineering context. For example, in her analysis of the Challenger space shuttle launch decision, Diana Vaughan [30, 31] draws attention to the role of intuition in forming ethical decisions. In conditions that went beyond previous experience, Roger Boisjoly and others had the correct intuition about potential risks. However, this intuition was discounted as a lack of "real data." The challenging situations highlighted in ethical case studies involve weighing explicit and tacit knowledge against a diverse range of considerations.
- In discussions of the ethics of **artificial intelligence** (AI) in the course, students have expressed particular concern for the effect of AI on the human mind. This concern has motivated class discussion on the relation of AI to human intelligence. In an important early critique of AI, Hubert Dreyfus highlighted the difference between AI and the function of the human mind [32]. Dreyfus outlines four assumptions that underlie persistent optimism about the capabilities of AI. Building on assumptions of the brain operating as a computer-like processor, the *epistemological assumption* is that "all knowledge can be formalized," and thus expressed in terms of logical relations. Dreyfus leans heavily on

Polanyi's epistemology, such as the importance of subsidiary awareness [32, p. 103] and indwelling [32, p. 252, 254]. Indeed, Polanyi [19, p. 261] had already responded to early claims of Turing by emphasizing the importance of tacit knowledge, which cannot be formalized.

Through the activities included in the epistemology unit, students work to describe "scientific knowledge," and produce a description that characterizes contemporary epistemic values. Discussion of elements of Polanyi's epistemology – tacit knowledge, focal vs. subsidiary awareness, the relation of knowledge to belief – expose some of the limitations of common assumptions. The connections given above provide concrete examples of how epistemic values play into the relationship between technology and soceity, as well as professional engineering ethics.

Course evaluation and discussion

Student evaluation of the class described above was obtained through two surveys and an interview, as listed below. These qualitative instruments were designed to give an understanding of student responses to the course and epistemology discussion class for the purpose of course improvement. They are mentioned here as background for the subsequent discussion.

1. **End-of-class survey:** Students completed this paper survey during the last ten minutes of the epistemology discussion class period. The survey asked students to (1) summarize the main points of the discussion, (2) list any parts of the discussion that made sense, and (3) list any parts of the discussion they found problematic for any reason. In the 21 responses for spring 2025 and spring 2026, students demonstrated an understanding of the point that human knowledge goes beyond what is objective or can be quantified. Half of the respondents mentioned tacit knowledge as a concept that made sense or was appreciated. Students gave a variety of responses as to what was problematic, with several mentioning the difficulty of connecting the concepts with specific examples.

2. **End-of-course survey:** Students were given time to complete this online survey during the final class of the semester. The survey included six open-ended questions asking students to indicate which course assignments and activities contributed most or least to their learning. This survey did not include specific mention of the epistemology discussion, but provided a place for the student to comment on it, if it stood out as a particularly valuable or otherwise. The 17 responses for spring semesters 2023-2025 were generally positive, with most students expressing appreciation for the discussion format as well as the class content. The epistemology discussion was not mentioned in responses to questions about activities contributing most or least to learning.

3. **Follow-up interview:** Students who had completed the course in the previous 6 - 30 months were asked to participate in a short evaluation interview. During the semi-structured in-person interview, students were asked initial general questions about the class: what they remembered and what stood out as beneficial. Students were then asked for feedback about the epistemology discussion: first without any reminder of the topics, and then with a reminder of the main topics if needed. Responses of the 15 students interviewed was consistent with the end-of-course survey results, in that students had positive recollections

of the course format and content. Most students mentioned the case study discussions or their own facilitation of these case studies as a memorable part of the class (11 of 15). Several specified that the most memorable was the discussion format of the class, or the opportunity to discuss with peers having different perspectives (6 of 15). The debate on technological determinism was most frequently mentioned as the most helpful class assignment (10 of 15), with several citing the opportunity to engage strong opposing positions in a respectful context. Most students said they did not remember the epistemology discussion, and that it was not something they had thought of since. However, after a reminder of the discussion topics, some expressed a vague recollection of the discussion (3 of 15) or mentioned one of the discussion topics (6 of 15).

Although evaluations demonstrated that longer term student recollection of the epistemology discussion was lower than hoped for, this is not a surprising result. Student responses (to 2 and 3 above) tended to emphasize core course content (ethics case studies or technology and society topics) and major course assignments. As a supporting single class unit without an associated major assignment, the epistemology discussion was designed to contribute to a deeper understanding of other core course topics.

Student participation during the epistemology class discussion and responses at the end of the class (survey 1 above) indicate that students were able to engage well with epistemological concepts, as presented with minimal philosophical jargon. Students appreciated the importance of tacit knowledge and its importance to technical and scientific knowledge, as well as other areas of human knowledge. Connections between the epistemology unit and the rest of the course, such as those described in the previous section, have been the focus of recent changes – and remain a priority for ongoing improvement. These specific examples have helped improve student engagement with this unit and comprehension of the content.

As noted above, student responses to the follow-up interview emphasized the value of class discussions. Many indicated the value of engaging with peers on difficult and contentious topics, as something that stimulated learning and helped them appreciate opposing views. Several also mentioned that this kind of interaction seems impossible in other social contexts ("You can't debate anything these days!"). Several of the studies cited above [2, 11] note the value of open-ended discussions of complex problems to helping students think beyond simple binary solutions. In this context, engaging in discussion on these complex ethical questions is perhaps the most valuable to the development of their personal epistemologies, while explicit treatment of epistemological questions plays a supporting role.

Conclusions

The work of Michael Polanyi has been used to pay explicit attention to epistemology in the context of an engineering ethics class. The implicit epistemologies of students have similarities to positivist epistemology, as illustrated in descriptions of the nature of scientific knowledge. Polanyi's epistemology addresses many of the shortcomings of positivism, and does so with a basis in ontological realism, which is considered important by many working in science and engineering. Polanyi provides a framework for considering non-objective knowledge, personal commitment, and the role of authority or belief in learning. He demonstrates the importance of tacit knowledge to everyday knowing as well as scientific knowledge and discovery.

Students engaged well in the epistemology discussion activities included in the course. Evaluations showed this engagement is matched by comprehension of tacit knowledge and other concepts discussed in the class. However, retention of these ideas to the end of the class or later in subsequent semesters is low. Ongoing development is focused on strengthening the connection between the epistemology unit and the rest of the course material, including case studies. As students understand the characteristics and limitations of contemporary epistemologies, they can understand the role of epistemic values in ethics case studies. They are also thereby equipped to appreciate the critiques of technology's role in society, which often rely on epistemological observations. The explicit discussion of epistemology also supports the development of a more nuanced and robust personal epistemology, as students engage in peer discussions of complex ethical questions and appreciate the role of epistemic values.

References

[1] C. Whitbeck, *Ethics in engineering practice and research*, 2nd ed. Cambridge: Cambridge UP, 2011.

[2] W. G. Perry, *Forms of intellectual and ethical development in the college years: a scheme*. Jossey-Bass, 1970.

[3] P. M. King, "How do we know what we know?; Why do we believe what we believe?" *Lib. Educ.*, vol. 78, no. 1, pp. 2–9, 1992.

[4] P. M. King and K. S. Kitchener, *Developing Reflective Judgment: Understanding and Promoting Intellectual Growth and Critical Thinking in Adolescents and Adults.* San Fransisco, CA: Jossey-Bass, 1994.

[5] M. Schommer, "Effects of beliefs about the nature of knowledge on comprehension," *J. Educ. Psychol.*, vol. 82, no. 3, pp. 498–504, 1990.

[6] M. B. Paulsen and C. T. Wells, "Domain differences in the epistemological beliefs of college students," *Res. High. Educ.*, vol. 39, no. 4, pp. 365–384, 1998.

[7] J.-C. J. Jehng, S. D. Johnson, and R. C. Anderson, "Schooling and students' epistemological beliefs about learning," *Contemp. Educ. Psychol.*, vol. 18, no. 1, pp. 23–35, 1993.

[8] B. K. Hofer and P. R. Pintrich, "The development of epistemological theories: Beliefs about knowledge and knowing and their relation to learning," *Rev. Educ. Res.*, vol. 67, no. 1, pp. 88–140, 1997.

[9] G. Clarebout, J. Elen, L. Luyten, and H. Bamps, "Assessing epistemological beliefs: Schommer's questionnaire revisited," *Educ. Res. Eval.*, vol. 7, no. 1, pp. 53–77, 2001.

[10] B. K. Hofer, "Personal Epistemology Research: Implications For Learning and Teaching," *Educ. Psychol. Rev.*, vol. 13, no. 4, pp. 353–383, 2001.

[11] R. M. Marra, B. Palmer, and T. A. Litzinger, "The effects of a first-year engineering design course on student intellectual development as measured by the Perry scheme," *J. Eng. Educ.*, vol. 89, no. 1, pp. 39–45, 2000.

[12] N. L. Frye, D. Montfort, and S. Brown, "Personal epistemology and sophomore civil engineering students," in *ASEE Annu. Conf. Expo. Conf. Proc.* Atlanta, GA: ASEE, 2013, pp. 23.963.1–11.

[13] A. Biglan, "The characteristics of subject matter in different academic areas," *J. Appl. Psychol.*, vol. 57, no. 3, pp. 195–203, 1973.

[14] J. Cruz, N. Bruhis, N. Kellam, and S. Jayasuriya, "Students' implicit epistemologies when working at the intersection of engineering and the arts," *Int. J. STEM Educ.*, vol. 8, no. 1, 2021.

[15] M. Borrego, “Conceptual difficulties experienced by trained engineers learning educational research methods,” *J. Eng. Educ.*, vol. 96, no. 2, pp. 91–102, 2007.

[16] J. S. Cicek and M. Friesen, “Epistemological Tensions in Engineering Education Research: How do we Negotiate Them?” *Proc. - IEEE Front. Educ. Conf.*, 2018.

[17] D. Montfort, S. Brown, and D. Shinew, “The personal epistemologies of civil engineering faculty,” *J. Eng. Educ.*, vol. 103, no. 3, pp. 388–416, 2014.

[18] E. G. Guba and Y. S. Lincoln, “Competing paradigms in qualitative research,” in *Handb. Qual. Res.*, N. K. Denzin and Y. S. Lincoln, Eds. Thousand Oaks, CA: Sage, 1994, ch. 6, pp. 105–117.

[19] M. Polanyi, *Personal knowledge: Towards a post-critical philosophy*, enlarged e ed. Chicago, IL: University of Chicago, 2015.

[20] ——, *The tacit dimension*. Chicago, IL: University of Chicago, 2009.

[21] M. J. Nye, *Michael Polanyi and his generation: Origins of the social construction of science*. Chicago, IL: University of Chicago, 2011.

[22] M. Polanyi, *Science faith and society*. Chicago, IL: University of Chicago, 1946.

[23] M. Olssen, “The epistemology of constructivism,” *Access Contemp. Issues Educ.*, vol. 13, no. 2, pp. 82–94, 1995.

[24] E. Von Glasersfeld, “The radical constructivist view of science,” *Found. Sci.*, vol. 6, no. 1-3, pp. 31–43, 2001.

[25] R. N. Boyd, A. Fine, C. Glymour, I. Hacking, L. Laudan, R. Laymon, J. Leplin, M. Levin, E. McMullin, H. Putnam, and B. C. van Fraassen, *Scientific realism*, J. Leplin, Ed. Berkeley: U of California Press, 1984.

[26] L. Laudan, *Beyond positivism and relativism: Theory, method, and evidence*. Boulder, CO: Westview, 1996.

[27] E. L. Meek, *Longing to know: The philosophy of knowledge for ordinary people*. Grand Rapids, MI: Brazos, 2003.

[28] T. Roszak, *The making of a counter culture: Reflections on the technocratic society and its youthful opposition*. Garden City, NY: Anchor Books, 1969.

[29] J. Ellul, *The technological society*. New York: Knopf, 1964.

[30] D. Vaughan, *The Challenger launch decision*. Chicago, IL: University of Chicago, 1996.

[31] C. Buck, “Go or no go: the Challenger legacy,” 2014. [Online]. Available: https://www.nytimes.com/interactive/2016/01/29/science/space/challenger-explosion-30-year-anniversary.html

[32] H. L. Dreyfus, *What computers still can’t do: A critique of artificial reason*. MIT Press, 1992.