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On Teaching Tacit Knowledge in Engineering Design and Professional Practice*

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The tacit knowledge associated with the application and integration of codified knowledge, personal experience, and the fundamental technical engineering knowledge is typically not developed in engineering students as a result of their coursework. Consequently, engineering students are not fully equipped for the demands of design even if their project requires largely codified knowledge. They require significant guidance and mentorship to describe design bases in their own words, to develop criteria for plausible solutions and then to research, identify, and synthesize plausible solutions. For experienced practitioners, this tacit knowledge is inherent to process, systems, and product design and is fully internalized. Filling or partially filling this knowledge gap comprises the invisible curriculum in undergraduate engineering design education. In this contribution, we describe how tacit engineering and engineering design knowledge is developed in our process design courses, how we structure implicit learning experiences, attempt to improve learning outcomes, and better prepare our developing engineers for early practice. Practical design projects, instructors with diverse knowledge and experience, a flipped course design (permitting intensive face-to-face interaction, mentorship, and creating opportunities to tell engineering stories during classroom sessions), individual and team assessment, and modeled interactions are used to create meaningful engineering experiences that help students develop their knowledge and understanding of the tacit curriculum. We provide reflections on our experiences. We expect our contribution to be of value across all engineering disciplines, and for professional practice development more broadly.

Keywords: chemical engineering; leadership; professional; tacit knowledge; invisible; curriculum; process; product; reflection; metacognition; design; course; practice; teaching; learning; industry; academia; links; transitions

1. Introduction

Chemical process design is taught as two sequenced courses in the fourth year of our chemical engineering program. Engineering fundamentals and professional skills are integrated in these courses and CEAB graduate attributes [1] are measured. Engineering design is where both students and practicing engineers employ a "hidden" or tacit curriculum including professional practices, contextual insights, and metacognitive processes [2–4]. The CEAB graduate attribute for design specifies "an ability to design solutions for complex, open-ended engineering problems and to design systems, components or processes that meet specified needs with appropriate attention to health and safety risks, applicable standards, and economic, environmental, cultural and societal considerations." [1] In order to demonstrate this graduate attribute, students must integrate their fundamental knowledge and understand the connections between what may have been learned as unrelated topics. Students must begin to determine and apply evaluation criteria and decide whether or not something is plausible in a way that an experienced engineer might. Our project-oriented design courses build communities of practice, natural extensions of the Community of Inquiry (CoI) framework [1], recognizing the importance of social and cognitive presence in instructional settings for professionals. Successful student groups demonstrate proficiency in most CEAB graduate attributes and have an intuitive and/or an experientially developed understanding of tacit design knowledge and sense making. As tacit knowledge is not often explicitly included in curricula and information technology reduces the importance of information recall, an analysis of effective techniques students may use to gain and apply tacit knowledge is a valuable contribution to evolving engineering education. Engineering graduates enter a competitive, often volatile profession. An intentional and evidence-based approach to teaching the associative skills necessary to solve complex contextual problems would be a benefit to their engineering education [6].

In this paper instructor and course designers' CoI perspectives illuminate the ways in which tacit engineering and engineering design knowledge are developed in our process design courses. Our current contribution builds on a previous work focussing on the community of practice course structure and the shift towards innovation type design projects. It includes a structural and content analysis with student reflections and perspectives surrounding learning experiences reflective of an internship

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in an innovative engineering firm [7]. This prior work highlighted the importance of mimicking the human, social, and cultural factors supporting information transfer and innovation in such an engineering design firm as part of the student design team learning experience. These factors include interaction with industrial advisors and others from a larger engineering community of practice. Student comments typically reflect positive affective belonging and engagement in the design courses structured in this manner [7]. Instructors and teaching assistants with industrial experience who can elucidate tacit knowledge are sought and retained; project sponsors and instructors intentionally simulate an industrial community of practice [8] to support practical experience acquisition. Our current contribution examines their perspectives in more detail and how their perspective informs the continual improvement process. Course design introduces elements of the invisible curriculum alongside the fundamental and explicit knowledge requirements for engineering design while retaining structural elements familiar to students; there are still exams and assignments, the security of a familiar institutional relationship, but with the inclusion of "gray areas" and structured mentorship that will dominate their early professional practice, post graduation.

2. Background

2.1 Tacit Knowledge and Experience

Michael Polyani is credited with the term tacit knowledge [9]. Polyani describes tacit knowledge as the implicit knowledge that solves the paradox outlined by Plato in the Meno. The essence of the paradox is that if all knowledge is explicit then we cannot identify a problem or look for its solution, yet there are problems and we do look for solutions [10]. This knowledge is termed as implicit or tacit knowledge and is exemplified by Polyani in the Tacit Dimension as the human ability to recognize a face; to see a problem and then to solve it; to develop the knowledge of how a tool feels in one's hand and to use it with skill; to have personal experience and to use it to create something. For each of these cases, the transfer of the requisite knowledge is not easily enabled. The knowledge may be described as personal, private, and not necessarily available for conscious introspection [9]. The natural acquisition of language and social behaviour where the knowledge about complex stimulus domains is acquired largely without conscious control are examples of implicit learning. There are underlying neurological mechanisms responsible for the acquisition and retention of implicit or tacit knowledge [9].

2.2 Tacit Knowledge and Engineering Design

A novice engineer may not be equipped for the demands of design even if the nature of the project requires largely codified knowledge that has been explicitly written down [4]. The tacit knowledge associated with the application and integration of codified knowledge, personal experience, and the fundamental technical engineering knowledge base [1] described in the first graduate attribute may not yet have developed. For an experienced practitioner, these internalized relationships are inherent to process, systems, and product design [11]. In addition, the ability to contextualize the problem in a specific frame may lead to expertise. Expert designers have a tendency to spend less time on problem definition and impose their particular frame and context on the problem where novice designers are more likely to employ a trial and error approach [13]. Expert designers may also take a systemic view of the problem, become solution focussed, and spend less time on problem definition and ideation than a novice designer [11–13]. In our experience and teaching practice, students do not formulate design problems or the context on their own – instructors do. For many students, the fourth year design course marks the first time they have been asked to describe a design basis in their own words, develop the criteria for plausible solutions, and then research, identify, and synthesize plausible solutions. This process of problem framing often requires significant guidance and mentorship in order to support skilful use of the design process. If the design process is conceived of as a tool, instruction on use and care of the tool is limited, students must actively engage in the application to appreciate where they require either additional practice or additional knowledge.

Tacit knowledge in engineering disciplines is recognized as an untapped resource, inherently valuable but often difficult to describe [14, 3]. For process designers, tacit knowledge in this context includes a practical and operational understanding of the equipment used in process design, chemical thermodynamics, hydraulics, utilities, control systems, hazard identification, the use of safety instrumented systems, fluid and equipment interactions, operating procedures, along with logical reasoning and the metacognitive skills required to manage the design and project process. Tacit knowledge in chemical product design includes understanding the end uses for the product, the demands and characteristics of the product users in order to define the specifications of the product. Organizational structures that engineers work within also require explicit and tacit knowledge that comes from practicing what has been learned from experience in areas such as leadership, management, and incident investigation processes [15–17]. In addition, tacit knowledge can include aspects of *operating* technology as described by Polyani where a manufacturing process made quality products in one location and flawed products in another with essentially the same process equipment [3]. The tacit knowledge of the manufacturing process had not been transferred. Similarly, the tacit knowledge of the use and care of the engineering design process is a critical aspect of engineering design education.

2.3 The Role of Instructors with Industrial Experience

There is a critical distinction between involving professionals in a simulated design environment and the early career mentoring that will be experienced in the first years of professional practice, particularly in the context of trends in corporate management that focus on process and compliance [18]. Final-year engineering students are typically positioned in an emergent phase of professional identity development that Arnett [19] describes as "Emerging Adulthood", a psychosocial view of identity construction explored specifically in relationship to occupations. Bringing engineers with industrial and practical experience into the design classroom, as instructors and teaching assistants, is an effective way to connect students with tacit design knowledge and the invisible curriculum.

It is important that design instructors appreciate the dual role they play in identity development, positioned in the familiar-to-students place of authority as instructors but also as peers and fellow professionals. Huff [20] explores the progression in identity development among undergraduate engineering students and offers an important insight to instructors of fourth year courses; the students cautiously identify as engineers, at a time when the "affirmation of those who matter" [21] is of utmost importance. Practitioner-instructors are not only cast as role models or examples, nor are they simply cast as the absolute authority in the teacher-student dyad; they are also members of the collective that the students need to complete their professional identity development. Turato et al. [22] describe the impact, positive and negative, of early career mentors in the higher-stakes environment of early practice, and reinforce the ideas summarized in Hyldgaard Christensen et al. [23] that the construction and maintenance of professional identity is critical in safeguarding the social role of professions.

Although there is a core design and project management process where engineers use and apply explicit fundamental concepts and techniques to design, there are a variety of stakeholder perspectives and perceptions that must be integrated and accounted for in the development of a design and in the design requirements at the engineering practice level [6]. Knowing which standards and practices might apply to which circumstances is not a matter of reference or checklist; standards and practices are strongly influenced by individual perspective, discipline bias and training. The process of testing, questioning, and responding to challenges is a foundational element of engineering practice. Creativity, flexibility, and agility of thought are required, yet challenging to introduce, in content-heavy fundamental courses [23]. The intentional formation of a community of practice, with reinforcement by instructor practitioners introduces the challenges of real world practice in the secure and familiar context of an academic course [16]. This constitutes an intermediate step for students that transfers tacit knowledge and uncovers the invisible curriculum.

2.3 The Role of Storytelling and Case Study Analysis in Passing on Experience

Stories of incidents and failures, stories of system operation, stories of innovation, stories of how and why knowledge is codified, stories of ethics, and stories of how design is done are told by engineers, operators, instructors, and students. These narratives are passed on to engineering students and recent graduate engineers who may have not yet heard them on an ongoing basis. Storytelling helps to make the personal and private aspects of tacit and implicit knowledge accessible to others. While not codified, stories provide us a window onto the experience and tacit knowledge of others [24] especially if we are able to suspend judgement and critically examine them. Stories promote the development of personal knowledge, albeit not to the same extent as lived experiences. The role of incident case studies in process safety management and design is an important factor in the development of tacit knowledge in engineering students [25]. Telling the story of the structure of wicked design problems [26] allows for insight into the complex problems society currently faces. Telling stories of ethics and professionalism affords insight on the expected behaviours of professional engineers [27, 28].

3. Course Delivery Method

3.1 Design Course Description

All materials and course delivery approaches for the courses have been developed or redeveloped over the past ten years by practicing professional engineers. The course design is based on a flipped and blended approach deliberately chosen to preserve and promote frequent interaction among students and between students and instructors and teaching assistants (TAs). Short topics regarding teaching and cognitive development are incorporated into weekly lectures, encouraging students to be intentional in their own learning. Students are asked what they think, how they plan to solve something, and what their approach is before advice is offered.

Design projects are prepared by the course instructors in collaboration with practicing engineers. Project topics are developed in response to current global industrial trends, current operational problems, operationalizing and/or commercializing research, benchmarking processes, scale up of processes designs, and enhancing the efficiency of existing process designs [7]. Occasionally students bring their own projects that they have identified during a work term.

Students are actively prepared for interactions with industry project sponsors. They are encouraged to plan for their interactions and to elicit information they will need during the project cycle. Students are assigned personal evaluation tasks both prior to and during the course as well as peer and team evaluations. Personal and team evaluations and reflections are built into the course as metacognitive cycles [7]. Each of three metacognitive cycles focuses on the planning and the production of a milestone project deliverable and ends with individual students and team of students reflecting on their achievement, how well they performed and how they might improve in a structured manner [7, 29]. A midterm exam offers a unique personal evaluation opportunity; the first pass at the exam is made individually, but the second pass involves design groups. Students may choose to accept either the individual mark or include a portion of the group mark. Under time constraints with the opportunity to improve their final grade substantially, students are well-served by evaluating themselves honestly and strategically deploying group members according to the strengths of each and exchanging information efficiently.

3.2 Design Course Implementation

Teaching is inductive and deductive and done in the context of a community of practice. Although the course descriptions include explicit knowledge topics, the courses focus on the contextual application of the knowledge, development of engineering practice, self-evaluation, and life-long learning. Lab assignments parallel early career assignments and are based on the analysis of a benchmark process plant that is developed week over week, beginning with the basic flow sheet development and ending with a business case analysis. Lab assignments are completed in teams, using a standard industrial process simulation package (VMG Symmetry) with open access to electronic and textbook resources. Interaction between teams is encouraged, and instructors and teaching assistants facilitate conversations and information sharing. Online resources are applied thoughtfully, with video and text references available as assignments are released. Lectures focus on application; topics are effectively summaries of prior coursework and include short quizzes and practice calculations that reinforce the real-world context. Instead of a textbook using a theoretical pump curve, students are asked to evaluate a fluid moving problem using a vendor manual with multiple product offerings.

As the course progresses students simultaneously choose industry-sponsored projects and apply their skills and knowledge to a new problem with concurrent lectures offering an active learning theoretical review and the lab sections proceed with a controlled design life cycle. This nested approach is very similar to most early career assignments, where engineers are asked for technical information while progressing multiple projects at various stages of development in different roles. Most students are enrolled in a full-time course load alongside the design course, and individual time management is key to success. Students are asked to plan their project, as well as submit plans for each lab assignment to reinforce the community element; while a single student may enjoy completing their work immediately before it is due, this approach doesn't work well in groups where different deliverables are sequential. This tacit knowledge is structured in the experience of the course as students take on greater responsibility for the management process from the first to the second Chemical Engineering process design course. Ongoing efforts are being made to include tacit knowledge earlier in the engineering program. For example, tacit knowledge is now included explicitly in Success in Engineering and Engineering Design, two first year courses taken by all engineering students, recently redesigned from previous offerings and offered for the first time last year.

3.3 Design Course Continual Improvement

Continual improvement is a key requirement of the Canadian Engineering Accreditation Board and a focus for the Chemical Engineering process design instructors [29]. Voogt et al. [30] use structural equation modelling to describe an analogous process in medical education; that of the resident. A teacher-practitioner without significant institutional authority may not "speak up" to voice suggestions for improvement. Design instructors actively seek input before, during and after each iteration of the design courses. The course design and community of practice approach actively involves instructors, project sponsors and teaching assistants in ongoing improvement [7, 29]. Active involvement of graduate students in teaching roles, not simply assignment grading, further reinforces the idea that everyone involved in the course is an engineer, and a member of the same community of practice. All are invested in the success of the students' transformation to engineers-in-training and their successful transition to the workplace.

4. Reflections and Improvements

Reflection is a metacognitive skill [31, 32] and a professional skill [33, 34]. It is essential for the cultivation of tacit or implicit knowledge in individual engineers and engineering students. Reflection is an art and a practice that enables us to make sense of our experience and reconcile it with the codified and fundamental knowledge that are inputs to our personal and private tacit engineering knowledge. There is a certain element of conscious control of reflection and to a certain extent it happens at an unconscious level as a result of our experiences [9]. Cultivation of student experiences to encourage conscious and unconscious development of tacit knowledge where students may check their perceptions with instructor and teaching assistant mentors is a part of how we teach. The following section comprises our reflections on our community of practice. All design instructors are professional and practicing engineers.

4.1 Instructor 1 Reflection

I am an engineer who became an academic later in my career. I look forward to teaching process design every term. I find going back to school every year exciting. I am keen to see what the students will think of the design projects we have developed for them to engage with. I am eager to help them learn about the design process and to watch them develop engineering identities. I enjoyed engineering as a chemical engineering undergraduate student, as a part time mechanical engineering graduate student, working full time at an operating company, as I became a professional engineer, as a consultant, and finally when I came back to university to teach. I became part of the process design teaching team and launched a new phase of my career as an academic. I am a lifelong learning enthusiast. My goal is to share my enthusiasm for engineering and my experience with the realities of complex engineering design, operation risk, and failures with students. My other goal is to help students begin to understand what engineering practice is and then to transition to engineering practice.

When I first started teaching, I realized all our students were capable. They are all intelligent and put in effort. I noticed some put in more effort than others, some knew what engineers do and some had a developing an engineering identity. They had a clear picture of what they were aspiring to be. Others really did not know what an engineer did or how to become one. For the most part, our design students all come to classes – whether or not they are always engaged or developing skills for engineering practice was a topic for debate and improvement. I wondered why not all students "get it" or are as capable of integrating knowledge from their other classes and applying it in the engineering design process. I became a part time MSc student again so I could study the education process from the perspective of the measuring student graduate attribute achievement, as we shifted the design course from a lecture based project course to a blended and active learning delivery approach. When we taught the course material in a lecture format, students were far less engaged than they are now with a blended learning approach and a focus on developing engineering design practice knowledge and skills. For some students, there was still something missing from a teaching and learning perspective - even after we shifted to blended learning. I began a doctoral programme focusing on creating a learning culture and improving engineering design education from the perspective of developing the graduate attributes and professional identity embedded in a community of practice. I had learned the lectures we put together were helpful, but less important than being a guide and a mentor as students *experience* what engineers do in the design process and learn from it. Developing an engineering identity seemed to be one of the missing items for students. Students come to understand their role as engineers from mentors who demonstrate the practice of engineering and show them the consequences of engineering failures. Telling and relating such stories to their project work helps students to develop hazard identification skills and in turn better design options – a key part of their engineering mindset and professional development. In other words, missing pieces of the design curriculum are found in a structured experiential learning process where students develop explicit and *implicit* knowledge. Once students learn the sense making metacognitive process and use it explicitly, they are able to continue using it before and after they graduate. Students develop their tacit knowledge and make sense of the fundamentals by connecting them to real pieces of equipment and examining the interactions of mass, energy, and momentum in each piece of process equipment studied. Process simulation is an important tool for knowledge synthesis and integration. It is exciting to see students make connections and be able to apply them to new circumstances. I want *all* of our students to succeed and get legitimate A grades. They are all capable. It is really just a matter of how far along they are on the path to embracing an engineering identity, integrating their knowledge with their experience of the world, and building confidence in their ability to frame design problems so a solution can be developed. All items supported by positive interactions with 'those who matter' in a community of practice.

4.2 Instructor 2 Reflection

I have taught Chemical Engineering process design for three decades. Over this time, I have observed an increasing need to include tacit knowledge explicitly in our design curriculum. Early on, students were responsible for obtaining engineering summer employment on their own. They developed and then worked their personal network of professional engineering contacts (engagement with active local chapters of professional societies that actively recruited students, recent alumni). Students relied more strongly on one another than they do currently and were more invested with one another socially. Students were engaged more deeply and consistently with the engineering profession from an earlier stage in their education. At that time tacit knowledge was transferred informally and organically from one "generation" of students to another, whether through storytelling or direct engagement. The community of practice was small and tight knit. There was limited need for explicit inclusion of tacit knowledge in the formal design curriculum. Fast forward to 2020. Class sizes are large; local sections of professional societies are less active, where they still exist, and are no longer a focus for professional life; students rely on co-op/employment offices to identify potential summer employment opportunities; student life is more diffuse; ties among student peers at the same or different stages of their program, and between students and recent alumni have loosened and are largely mediated by university staff. Explicit inclusion of tacit knowledge in the curriculum is essential. In between, I sensed a growing disconnect between my expectations of students' ability to handle open-ended design challenges and their actual ability to do so. Over time we increased the number, nature, and depth of interactions between students and practicing engineers, as class size grew, and took other steps to bridge student learning needs, but only more recently did we include tacit knowledge explicitly in the curriculum. I'm glad we did. The impact on student learning and professional development has been apparent.

4.3 Teaching Assistant and Instructor 3 Reflection

I found myself as a student again after a painful layoff, back in the buildings where I'd taken my undergraduate degree, in a bizarre state of deja vu. Offered a teaching assistantship in the senior design course, I leapt at the chance. The assignments for the design course were similar to deliverables prepared by early career engineers. I delighted in including reference links, diagrams and images in student assignments when they showed even a glimmer of interest in my subject area. I grinned when one of the students took me aside during an early lab activity and asked sincerely whether things were so "messy" in the real world; a process design problem with no obvious solution and many assumptions to be made. I enjoyed having stories for nearly every piece of equipment studied in the course; despite having been primarily a mechanical engineer, I had a surprising degree of relevant narratives for process engineering problems. Students always smiled when I would get excited, "this is the fun part! Isn't it great that we get to do this?"

Working as an assistant in this course, I began to realize that I had lost touch with the optimism and purpose that drove me through the early years of turnarounds and failure investigations, brushing coke dust off my face and scraping bitumen off my boots. We present the design course described in this paper as a type of bridge for students, between the familiar world of school and the challenging world of early career life, but it's a bridge for practitioners too. As detailed study of scientific theory expands my knowledge of my subject area, the opportunity to teach undergraduates expands my optimism and confidence in the profession. Several students made a habit of staying behind after lab sections to ask me questions about everything from the week's assignment to weighing different job opportunities. I may not have succeeded in communicating to every corporate manager that challenged me, but the stories I tell students arm them for similar battles. Engineers often work in relative isolation in modern business environments. This course showed me, beyond a shadow of a doubt, the value of a community of practice, not only for students, but for educators and practitioners. A teaching assistant doesn't need to be a marking machine, let loose from a connect-the-dots marking guide, students may find a potential peer; a reality that is more imminent than many realize. These lessons could have significant implications for managers of engineering departments as well as inform practices for teaching.

4.4 Improvements and Findings

Evaluating design projects requires assessment of gaps – areas where performance does not meet specifications. New iterations of a design arise from the identification and evaluation of gaps. Our instructor reflections offer three unique perspectives that delineate a widening gap. Engineering academic experience is unlike professional practice experience and the characteristic tendencies of both career paths appear to be divergent. In order to effectively bridge the gap and prepare students for professional practice, it is necessary to understand the reality of student life as well as the professional realities and responsibilities of both university based instructors and industry based professionals practicing engineering.

> "I learned a lot from this course, and especially from the advisor asking you to think by yourself, because it used to be: 'I'll tell you this, and you'll tell me that', but this time it was: 'you tell me what you think, or what's the option you have to accomplish this design' And that made me very motivated" (Student) [7].

Design projects conceived by industry-based practicing professional engineers and delineated by university instructors offer the structure of real-world interactions. The inclusion of practicing professionals supports the inclusion of the routines and cultural norms common to engineering workplaces in our design courses. The practice of technical challenge, which includes checking and peer review, is a key element of our course design. For example, the initial student design project deliverable, the project scope, occupies a significant amount of the course timeline and offers two opportunities for formal feedback and informal discussion. The initial submission is graded on a completion basis, reinforcing the idea that in engineering practice it is unrealistic to expect a first submission will meet the expectations of the client. Revisions are typically expected. Cycles of negotiation and revision are necessary to develop a shared tacit understanding of the problem to be solved. This threshold concept is challenging for students, who may come to design with some anxiety surrounding grades and achievement and struggle with formative assessments.

> "This course gave me confidence that I can be an engineer. Even though I didn't do as well as I hoped, this course taught me many intangible skills like leadership, adaptability, problem solving and on the spot thinking" (Student).

When academic institutions prioritize field experience as a teaching qualification and encourage field experience as part of undergraduate and graduate learning experiences, they recognize the intertwined nature of academic and industrial professional engineering practice and the value of integrating practical expertise into academic programmes. This implicit message is not lost on design students. Explanations and descriptions of design practices are complimented by realistic feedback and modeled interactions, which students can test and try as they develop their design projects.

> "Learning in that environment was actually really interesting, because some of the other students could have an insight that another may not, and a lot of the co-op students have worked in different areas, and when we talked about pumps or heat exchangers, they knew about them more than some of the traditional students. So, it was really nice to share the experiences and to start learning from other people, and start collaborating with them" (Student) [7].

Instructors with diverse knowledge and experience working jointly in a flipped course delivery model closely reflects the reality of professional practice, where projects have multiple stakeholders and contributors who do not approach concepts and tasks in the same way. Stakeholder meetings are not typically structured as information delivery and note taking. Active engagement from designers and stakeholders is vital to reaching the necessary shared understanding of the design problem, constraints, specification, and possible solutions. The lead instructor asking questions like "How would you identify this phenomenon in the field?" or "What do you think about this situation?" to prompt a contribution from a TA or co-instructor models the type of collaborative interaction necessary for students to elicit high quality stakeholder input from their clients in the capstone course and from project stakeholders as new graduates. Throughout the course this practical approach is apparent, with instructor debriefings following key student evaluations; student assessments and feedback are applied to determine areas of focus as the course progresses and between academic terms. The evolution of the design course demonstrates the importance of evaluation and re-design, as with any engineering project.

5. Conclusions

Tacit knowledge is an important aspect of chemical engineering design and engineering design in general. Tacit knowledge is generally not taught in the context of a lecture or structured laboratory experience where the learning objectives are specific to codified and fundamental knowledge acquisition and reporting on predetermined outcomes. Tacit knowledge is acquired in an experiential manner. When the experience is scaffolded, this allows for time for student reflection and multiple iterations and enrichment of the tacit knowledge acquired in the program. The transfer of tacit knowledge can be enhanced by the use of narratives, mentors, graduate students, industry practitioners, and student reflection. Continual improvement and modeling of reflection by the teaching team may normalize this activity for students as a part of professional practice.

References

1. Canadian Engineering Accreditation Board, *Canadian Engineering Accreditation Board: Accreditation Criteria and Procedures*, Ottawa, 2014.
2. Engineers Canada, *The Engineering Design Task Force Report*, 2020.
3. P. Nightingale, Tacit Knowledge and Engineering Design in *Philosophy of Technology and Engineering Sciences Handbook of the Philosophy of Science*, ed. Anthonie Meijers pp. 351–374, 2009, https://doi.org/10.1016/B978-0-444-51667-1.50017-3
4. S. Moran, Classic mistakes in water and effluent treatment plant design and operation in *An applied Guide to Water and Plant Effluent Design*, (Ch 28) pp. 317–323, 2018, https://doi.org/10.1016/B978-0-12-811309-7.00028-X
5. M. V. Jamieson and J. M. Shaw, Learning to Learn: Defining an Engineering Learning Culture, in *Canadian Engineering Education Association Conference*, (CEEA 2019), 2019. Doi: https://doi.org/10.24908/pceea.vi0.13707
6. N. D. Vaughan, D. R. Garrison and M. Cleveland-Innes, ONE: Conceptual Framework, in *Teaching in Blended Learning Environments: Creating and Sustaining Communities of Inquiry*, Edmonton: AU Press, pp. 7–18, 2013.
7. M. V. Jamieson and J. M. Shaw, Teaching Engineering Innovation, Design, and Leadership through a Community of Practice, *Education for Chemical Engineers*, **31**, 54–61, 2020. https://doi.org/10.1016/j.ece.2020.04.001
8. S. Gherardi and D. Nicolini, Safety in Communities of Practice, *J. Manag. Inq.*, **9**(1), pp. 7–18, 2000.
9. A. S. Reber, Tacit Knowledge, Psychology of in *International Encyclopedia of the Social and Behavioral Sciences*, eds. Neil J. Smelser and Paul B. Baltes, pp. 15431–15435, 2001, https://doi.org/10.1016/B0-08-043076-7/01492-3
10. M. Polyani, *The Tacit Dimension*, Doubleday and Co. Garden City, NY, 1966.
11. C. Atman, R. Adams, M. Cardella, J. Turns, S. Mosborg and J. Saleem, Engineering Design Processes: A Comparison of Students and Expert Practitioners, *J. Eng. Educ.*, **96**(4), pp. 359–379, 2007.
12. N. Cross, Expertise in design: an overview. *Design Studies*, **25**(5), pp. 427–441, 2004.
13. N. Cross and A. Clayburn Cross, Expertise in Engineering Design, *Res. Eng. Des. – Theory, Appl. Concurr. Eng.*, **10**(3), pp. 141–149, 1998.
14. L. Liu, Z. Jiang and B. Song, A novel two-stage method for acquiring engineering-oriented empirical tacit knowledge, *Int. J. Prod. Res.*, **52**(20), pp. 5997–6018, 2014.
15. W. J. Schell, Exploring the Conflict Between an Engineering Identity and Leadership in *Canadian Engineering Education Association Conference*. (CEEA 2018), 2018, DOI: https://doi.org/10.24908/pceea.v0i0.13100
16. M. V. Jamieson and J. R. Donald, Building the Engineering Mindset: Developing Leadership and Management Competencies in the Engineering Curriculum, in *Canadian Engineering Education Association Conference*. (CEEA 2020), 2020, DOI: https://doi.org/10.24908/pceea.vi0.14129
17. C. Belack, D. Di Filippo and I. Di Filippo, *Cognitive Readiness in Project Teams*, New York, NY: Routledge/Productivity Press, 2019.
18. D. A. Kennedy and M. Nur, The rise of Taylorism in knowledge management, in *2012 Proceedings of PICMET '12: Technology Management for Emerging Technologies*, 2012.
19. J. J. Arnett, Emerging Adulthood: The Winding Road from the Late Teens Through the Twenties, in *Emerging Adulthood*, (2), pp. 1–28, 2014.
20. J. L. Huff, B. K. Jesiek and W. C. Oakes, Psychological journeys of engineering identity from school to the workplace: How students become engineers among other forms of self, *Eng. Educ.*, vol. PhD, p. 325, 2014.
21. K. L. Meyers, *Engineering identity as a developmental process*, Purdue, 2009.
22. E. R. Turato, M. Schweller, E. Helmich, M. A. de Carvalho-Filho, G. L. Silveira and L. K. S. Campos, 'Speed up'! The Influences of the Hidden Curriculum on the Professional Identity Development of Medical Students, *Heal. Prof. Educ.*, 2018.
23. S. Hyldgaard Christensen, *Engineering Identities, Epistemologies and Values*, **21**, Cham: Springer International Publishing, 2015.
24. C. Schilcher, Tacit knowledge and storytelling, WMSCI 2009 – The 13th World Multi-Conference on Systemics, Cybernetics and Informatics, Jointly with the 15th International Conference on Information Systems Analysis and Synthesis, ISAS 2009 – Proc, **1**, pp. 150–154.
25. M. V. Jamieson, L. Lefsrud, F. Satarri and J. R. Donald, Engineering Safety and Risk Management: A Structured Case Study Approach to Investigating Chemical Process Safety, in *American Society for Engineering Education* (ASEE20) Paper ID 30956, 2020.
26. R. Buchanan, Wicked Problems in Design Thinking, *Des. Issues*, **8**(2), pp. 5–21, 2016.
27. G. C. Andrews, J. D. Aplevich, R. A. Fraser and C. G. MacGregor, *Introduction to professional engineering in Canada, Fifth edition*. North York, ON: Pearson, 2019.
28. R. Belanger and R. Pupulin, *APEGA Concepts of Professionalism*, 2004.
29. M. V. Jamieson and J. M. Shaw, A Continual Improvement Process for Teaching Leadership and Innovation Within a Community of Practice, in *American Society for Engineering Education* Annual Conference (ASEE 2019), 2019.
30. J. J. Voogt, T. W. Taris, E. L. J. van Rensen, M. M. E. Schneider, M. Noordegraaf and M. F. van der Schaaf, Speaking up, support, control and work engagement of medical residents. A structural equation modelling analysis, *Med. Educ.*, **53**(11), pp. 1111–1120, 2019.
31. D. Boud, R. Keogh and D. Walker (Eds), *Using experience for learning*, Society for Research into Higher Education University Press: University of Michigan, 1993.
32. D. Boud, R. Keogh and D. Walker (Eds), *Reflection: Turning experience into learning*, Psychology Press, 1985.
33. D. Schon, *Educating the reflective practitioner Towards a new design for teaching and learning in the professions*, San Francisco: Jossey-Bass, 1987.
34. D. Schon, *The reflective practitioner: How professionals think in action*,.. England: Arena, 1995.

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