



The role of undergraduate laboratories in the formation of engineering identities: A critical review of the literature



Authors:

Christine Winberg¹ Simon L. Winberg² 

Affiliations:

¹Professional Education Research Institute, Cape Peninsula University of Technology, Cape Town, South Africa

²Department of Electrical Engineering, Faculty of Engineering, University of Cape Town, Cape Town, South Africa

Corresponding author:

Christine Winberg,
winbergc@cput.ac.za

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Background: There was growing recognition worldwide by professional engineering bodies, engineering faculties and researchers on the need to pay attention to engineering students' emerging identities and how they were formed across the trajectory of undergraduate engineering programmes. An increasing number of research studies focused on engineering identity, including systematic reviews of the research literature.

Aim: Engineering laboratories were key learning spaces in undergraduate engineering programmes. In the laboratory, students learned to integrate theory and practice, engaged in problem-solving and applied experimental methods. The purpose of this critical review of the literature was to interrogate the impact that learning in engineering laboratories had on emerging professional identities across engineering disciplines and fields.

Method: This review built on and extended previous systematic reviews on engineering identity by studying pedagogies in the engineering laboratory through the lens of identity formation. Search terms were consistently applied to eight databases, which yielded 57 empirical studies, after the application of relevance and quality appraisal criteria. Two reviewers independently applied a socio-materialist theoretical framework of identify formation to each study and coded each of the studies into categories aligned with the theoretical framework.

Results: The findings of the critical review revealed the temporal, spatial, material, performative and discursive dimensions in engineering identity formation and showed that students' emerging identities could be affirmed and supported by appropriate laboratory pedagogies.

Conclusion: The critical review of the literature concluded that curricular and pedagogical interventions that were better aligned with the dimensions of identity formation were more likely to enhance students' identification with engineering.

Keywords: engineering; undergraduate laboratories; identity; ontological formation; socio-materialism; critical review of the literature; curriculum; pedagogy.

Introduction

Identity formation in the engineering laboratory

Undergraduate engineering programmes pose a range of challenges to students; as a result, much research in engineering education has focused on enhancing curricula, pedagogies and assessment in support of student success.¹ Whilst engineering studies are demanding and many students leave programmes where they have little chance of success, it is increasingly understood that many students choose to leave engineering programmes, not because of the high levels of challenge, but because they feel excluded and disengaged.^{2,3} Considerably fewer studies have addressed issues of institutional or departmental cultures¹ or interrogated the role that these may play in student attrition.⁴ Supporting emerging engineering identities has been understood as a proxy for inclusive forms of engineering education and retention across engineering programmes,⁵ and there is growing recognition worldwide by professional engineering bodies, engineering faculties and researchers of the need to pay closer attention to the engineering cultures that underpin curricular and pedagogical practices and their impact on student identities.^{4,5} It is the intention of this critical review of the literature to synthesise previous work through the lens of identity formation in order to understand how engineering identities emerge in undergraduate engineering laboratories.

Why the undergraduate laboratory?

Engineering laboratories are key spaces for identity formation; they bridge the 'theory/practice divide',⁶ enabling theory to be applied to engineering problem-solving and design,⁷ as well as revealing the scientific basis of engineering artefacts⁸ – whilst engaging students in experiments and active learning.⁹ Learning in an engineering laboratory tends to be more active than in classrooms and lecture halls and includes consolidating scientific and engineering concepts,¹⁰ developing engineering design abilities¹¹ and nurturing professional and social skills.¹² The undergraduate laboratory is important in preparing students for engineering practice beyond the university, as 'a sustainable society needs engineers who are familiar with experimenting and laboratory work'.¹³ Skills learned in the engineering laboratory, such as conducting experiments and tests, solving problems, designing and innovating, are key skills for professional practice. As the student's familiarity with the engineering laboratory develops, the values underpinning engineering identities emerge. The pedagogical value of engineering laboratories is well-supported by the literature,⁵ but the literature also warns that the engineering laboratory poses challenges.^{4,14} Whilst engineering laboratories are generally understood to be engaging and supportive spaces in which engineering identities can develop, they can also be unwelcoming and hostile environments in which some students feel excluded and isolated.^{2,15} From a socio-materialist perspective, the engineering laboratory is the site where future engineers are socialised, whilst the material practices of the laboratory community and what these enable or constrain are important to future engineers' sense of themselves as engineers. Despite evidence of the important role of the undergraduate engineering laboratory in the development of an engineering identity, laboratories have been understudied in the research literature.¹⁶ It is this gap that this critical review addresses.

Why identity?

Early studies understood engineering identity as self-evident, but more recent studies have paid attention to how engineering identities are enabled or constrained across engineering programmes. Identity is multiple, complex and layered; thus, students (and professional engineers) have personal and social identities as well as engineering identities.¹ Early identification with their profession is crucial for persistence amongst engineering students¹⁷; students who do not develop a sense of belonging, identify with an engineering field or perceive themselves as engineers are more likely to abandon their studies.^{4,14,18} Identification, or how students identify with engineering and are identified by others as an engineer, is 'formed out of a double-sided process of positioning ourselves and being positioned by others'.¹⁹ Imagining future jobs in an engineering field is a key part of students' identification with engineering.¹⁷ The development of an engineering identity is further supported when students see the relevance of their studies for their future career.⁹ Professional identities are built through shared experience and traditions, enabling a sense of membership, attachment and contribution.³

In their review of the literature on engineering identity, Patrick and Borrego claim that the concept of an engineering identity has not been theorised or measured and that the concept of an engineering identity has been conflated with other attributes such as an engineering 'mind-set', 'self-concept' or even with 'soft skills' more generally.¹ Definitions of identity in the literature can be summarised as 'seeing oneself as, or feeling like, an engineer'.¹⁶ This narrow definition does not take into account the cultural and material factors that shape how students become engineers. Indeed, despite recent understandings of identity as distributed and developing from participation in collective activities, the literature has not focused on the processes of acquiring an engineering identity. Identity formation is generally accepted as a central part of learning; identity emerges from the interrelationship between individual agency and the social organisation (or culture) in which individual actions are performed.²⁰ However, little is known about the ways in which engineering students construct professional identities in tandem with their learning, how they come to take on engineering values and how engineering identities emerge across the trajectory of undergraduate study. Whilst it is understood that identity is fundamental to membership of a professional community,²¹ most research studies with a focus on engineering identity have not traced the trajectory of becoming an engineer.^{1,21,22} This is precisely the issue that this review of the literature addresses and in order to do this, we appropriate the analytical lens of 'ontological formation'^{23,24,25} to examine engineering identity formation in the undergraduate laboratory.

A theoretical framework for identity formation

This study draws on socio-material understandings of identity formation in the engineering laboratory.²⁵ Socio-material approaches foreground the interplay between the material and social in the development of agency and identity.²⁴ Applying a socio-material interpretation to the current study suggests that the materiality of laboratories and their associated tools and technologies would enable certain practices and constrain others. Students coming into engineering disciplines and fields, particularly if they have not been introduced to engineering through family membership, schooling or other previous studies, will initially require guidance and support in laboratory practice,⁴ but are likely to become more proficient and expert as they become familiar with the routines of the laboratory.¹⁹ As new students engage in laboratory activities, eventually participating more fully as members of a community, shifts in their identity would be expected. It is the particulars of students' entry into, and development within, engineering laboratories that are of interest in this review of the literature, which necessitates a brief discussion on ontological formation.

Ontological formation

Identity develops across the fundamental categories of existence: time, space, materiality, performance and communication.²⁴ These ontological categories are

foundational to being human and can be relatively stable or, notably in formative years, volatile.²⁵ Being human means undergoing change over many trajectories. The ontological categories point to the different ways in which individuals and communities live in different temporal, spatial and material contexts, how they perform and communicate in relation to others and in relation to natural and human-made environments and how they make sense of their existence and identities.²⁴ Ontological formations are not standalone formations; they are iterative and co-exist.²⁵ Identity formations can also be prospective, that is, they can be influenced by new ideas and activities, so that new ways of being in the world can be imagined.²⁴ Thus, ontological formations are layered and intersecting rather than singular and distinct.²³

Ontological formations are impacted by 'a host of material-discursive forces'.²³ The process of learning to become a professional involves more than learning new knowledge; what is also important is 'all the crucial interactions' that students will experience that often 'fly in the face of any specific set of disciplinary concerns'.²³ These 'crucial interactions' are of importance in engineering identity formation and should be supportive and inclusive. Pickering describes ontological formations as 'dances of agency' that academic disciplines will 'seek to organise ... in a peculiar and distinctive way'.²⁵ Pickering argues that it is necessary to ensure 'islands of stability in the flux of becoming; configurations, socio-material set-ups, where some sort of reliable regularity in our relations ... is to be found'.²⁵ To understand students coming into engineering as a social encounter, Barad's call for a re-thinking of the social through the scientific is pertinent:

What often appears as separate entities (and separate sets of concerns) with sharp edges does not actually entail a relation of absolute exteriority at all. Like the diffraction patterns illuminating the indefinite nature of boundaries – displaying shadows in 'light' regions and bright spots in 'dark' regions.^{23(p. 803)}

The philosophical concept of ontological formation can be drawn on to understand how engineering laboratories might enable students with diverse social and personal identities to attain an engineering identity. Describing urban spaces that facilitate encounters across differences, James describes how 'locals and strangers should rub shoulders, sometimes painfully, as they move through in locally defined places'.²⁴ In an engineering laboratory, supporting students' ontological formations would entail planning activities that acknowledge the presence of different ontological orientations and their different trajectories of development. Accommodating multiple identities is not a strong feature of engineering education, although promising studies that affirm a diversity of engineering identities are emerging.^{3,14}

More immediately, useful tools for planning the kind of laboratory spaces and practices that a university might want to cultivate are necessary. It is proposed that tools to define and measure emerging engineering identities can be developed in terms of temporal, spatial, material, performative and discursive elements.

The temporal dimension of identity formation

Temporality is fundamental to the development of identity; at the most basic level, students' knowledge and skills develop with time and experience.²⁴ Constructive encounters between novice and more senior engineering students can facilitate the temporal dimension of identity formation.²⁶ The temporal trajectory is dynamic and iterative and not without challenges. In the flow of activity within an engineering laboratory, newcomers can be 'caught in the tensions between past histories that have settled in them and the present discourses and images that attract them or somehow impinge on them'.⁵

The spatial dimension of identity formation

Engineering laboratories are the 'persistent backdrop'⁵ against which students become engineers. They have thus been described as key socio-cultural spaces for engineering identity formation.⁵ The engineering laboratory is a context with a particular culture and taken-for-granted ways of being, doing and belonging. The 'micro-climates' of engineering laboratories can convey warmth, supportiveness and care or they can symbolically replicate 'forms of social segregation and devaluation that repeat legacies of racism in miniature'.²

The material dimension of identity formation

There is an abundance of tools, artefacts and devices in engineering laboratories for carrying out engineering work. Becoming proficient in the use of these tools has been identified as an indicator of professional identification.¹⁷ Students in engineering laboratories are engaged in 'forming relationships both with people and with the technological artefacts they design and build'.²⁷

The performative dimension of identity formation

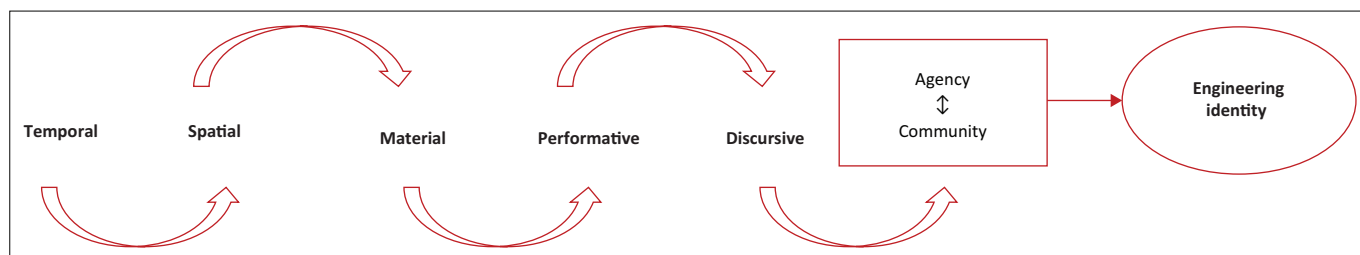
Identity is formed and shaped by practice and by the context of practice.²¹ For engineering educators, competent practice in an engineering laboratory predicts successful professional practice.¹⁰ Competence in the laboratory and identification with the norms of laboratory practices consequently determine who is considered to be an engineer.¹⁴

The discursive dimension of identity formation

The final key element in the process of identity formation concerns the tacit and explicit communication of engineering knowledge and values. Engineering communication is formally taught,¹⁹ but communication is also acquired as messages subtly embedded in everyday interactions.²⁸ Access to disciplinary discourses influences identity, particularly if the student is encouraged to engage with that discourse and gain mastery over its use.⁸

The above dimensions are presented in Figure 1 as a linear process for analytical purposes; the actual process is more complex, multi-layered and iterative.²⁴

Figure 1 shows that the ontological trajectory impacts individual agency and the individual's relationship with the community, that is, how a person is able to act in the world,



Source: Adapted from James P. Urban design for the global south: Ontological design in practice. In: Kalantidou E, Fry T. editors. Design in the Borderlands. London: Routledge, 2014; p. 101–118.

FIGURE 1: Ontological formation of engineering identity.

TABLE 1: The search strategy.

Search terms	Databases searched	Cross-checked
Engineer† AND laborator† AND ('engineer† identity' OR 'identification with engineer†')	ACM Digital Library	<i>ACM Transactions on Computing Education</i>
	ASEE Peer	<i>Advances in Engineering Education</i>
	IEEE Xplore	<i>IEEE Transactions on Education</i>
	SABINET	<i>African Journal of Research in Mathematics, Science, and Technology Education</i>
	SCOPUS	<i>Education for Chemical Engineers</i>
	Springer	<i>International Journal of Technology and Design Education</i>
	Taylor and Francis	<i>European Journal of Engineering Education</i>
	Wiley	<i>Journal of Engineering Education</i>

†, includes laboratory and laboratories.

in this case, within a professional community. Identity (whether positive or negative with regard to the engineering profession) emerges from how agency is enacted and how the community affirms or denies the enacted agency.

Methodology of the critical review

In this section, the approach to the critical review is explained, including the search strategy and search terms, the inclusion and exclusion criteria, as well as how the studies selected were critically analysed. We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology for critically reviewing the literature.²⁹ In common with all systematic reviews of the literature, a critical review presents a 'synthesis of a variety of literatures, identifies knowledge that is well established, highlights gaps in understanding and provides some guidance regarding what remains to be understood'.³⁰ A critical review is particularly apposite when scholars hold different views, as is the case in identify formation. The particular contribution of a critical review is to 'give a new perspective of an old problem, rather than simply paraphrasing what all other researchers and scholars in the field have shown or said in the past'.³⁰ The PRISMA critical review methodology comprises four steps: (1) identification of studies via a transparent and replicable search strategy, (2) justification of the inclusion criteria, (3) screening of the studies and data extraction and (4) a critical analysis of the studies.²⁹ It is the last step, the critical analysis of the studies, which distinguishes a critical review from a systematic review. In a critical review, the data extracted are coded and thematically analysed, drawing on a theoretical framework to provide a new perspective and theoretically informed insights into the studies reviewed.

Identification

Studies and reports use a variety of synonyms for identity, such as 'habits of mind',³¹ 'self-efficacy',³² 'professional identity',¹¹ 'engineering roles'³³ and so on. The authors piloted different terms before the final search terms were selected (see Table 1). Eight academic databases were searched and the search was cross-checked within journals, academic books and published conference proceedings, yielding 476 studies. Additional sources were found by searching the reference lists of the studies and a further 35 studies were added. Duplicates were removed, resulting in 391 articles, book chapters and conference proceedings. Table 1 shows a schematic representation of the search strategy.

Screening

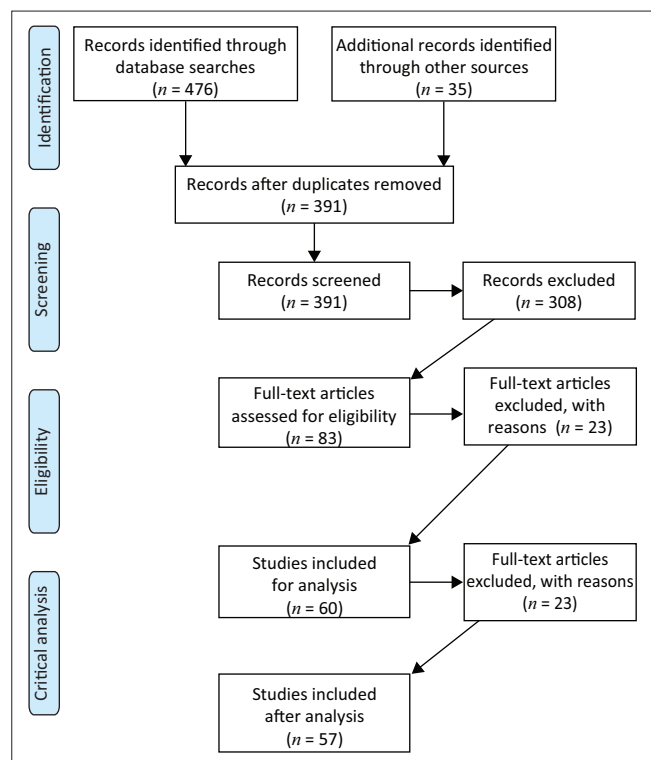
For the second step, screening, inclusion and exclusion criteria were applied to the 391 records (see Figure 2).²⁹ The abstracts were read by both authors in order to determine the relevance of the study to the research question, that is, whether the paper addressed the role of the undergraduate laboratory in engineering identity formation. Articles that were not relevant to the shaping of engineering identities through engagements in the laboratory were excluded from the study. Articles were also excluded if they were position papers, reviews of the literature, work-in-progress conference papers or very short papers (i.e. shorter than two pages). The screening process resulted in the exclusion of 308 studies and the inclusion of 83 studies.

Eligibility

The initial screening was based on a reading of the abstracts, which yielded 83 studies. The full texts of the 83 records that passed the initial screening process were then studied to determine their findings on the role of undergraduate engineering laboratories in students' emerging identities. In the process of close reading, it was found that some studies had been incorrectly included as they were not relevant to the research question. This resulted in the exclusion of a further 23 texts, resulting in 60 texts that addressed identify formation in the engineering laboratory.

Critical analysis

The 60 research studies selected for inclusion in the database addressed a range of issues with regard to the role of undergraduate engineering laboratories (both physical and



Source: Adapted from Evans N, Bausewein C, Meñaca A, et al. A critical review of advance directives in Germany: Attitudes, use and healthcare professionals' compliance. *Pat Educ Counsel.* 2012;87(3):277–288. <https://doi.org/10.1016/j.pec.2011.10.004>

FIGURE 2: Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow chart for the critical review of the literature.

virtual) in the formation of engineering identities. Following the in-depth critical analysis, three additional studies were removed because, upon closer examination, their focus was not on engineering identity formation. The final database for the critical review therefore comprised 57 studies. An Excel file was used for the database, which had the following column headings: (1) field (i.e. the area of engineering such as chemical, computer, etc.), (2) the names of the authors, (3) the date of the study, (4) the title of the study, (5) the abstract, (6) the context (i.e. the authors' affiliations and countries), (7) the research methodology, (8) the findings and (9) the full citation of the study.

The researchers used the ontological formation framework (Figure 1) to code the findings into categories that broadly indicated whether the study explicitly or implicitly referred to temporal, spatial, material, performative or discursive elements of identity. For example, the study by Butterworth and Branch²⁶ on collaborations between 'seniors and freshmen on senior capstone projects' was coded as 'temporal' because it focused on 'multigenerational' collaboration and the role of senior engineering students in inducting first-year students into laboratory practices. In contrast, Craig's study⁹ focused on the spatial affordances for 'personal discovery learning' in the laboratory and its impact on engineering identity formation; Craig's study was thus coded as 'spatial'.

The researchers worked independently to code the studies as described above, achieving approximately 70% consensus following the first coding. The authors then jointly re-coded

all the studies and negotiated the final categories by consensus. In the context of the study, consensus required agreement on the key findings of the study by both authors. It should be noted that most of the articles reviewed included more than a single element of identity formation: for example, articles that discussed the impact of spatial features (e.g. spatial arrangements for group work) usually addressed material dimensions (e.g. tools and artefacts) as well. However, articles tended to emphasise a particular dimension (either spatial or material) and were coded according to the more prominent dimension.

Following the close reading and coding of the articles, key concepts were identified and their connections were mapped across the studies in the database. This synthesis of the findings was conducted by comparing, contrasting, interpreting and drawing conclusions. Thus, the broad categories of time, space, materiality, performance and discourse that were initially identified across the studies were further developed. The final step of the synthesis was to find patterns of identity formation, to add depth and detail to the theoretical categories of ontological formation in the engineering laboratory and to extract common pedagogical practices in support of emergent engineering identities.

The research studies were conducted across a wide variety of contexts: Australia, Canada, China, Denmark, India, Ireland, Italy, Japan, Malaysia, Romania, South Africa, Sweden, the United Kingdom and the United States. Most of the studies were evaluation studies (28/57) in which a laboratory intervention intended to promote identification with engineering was assessed. There were five case studies, most of which focused on a single student or small group. There were eight interview-based studies and seven surveys. Nine of the research articles drew on ethnographic and observational methods.

Ethical considerations

Fundani Research Ethics Committee (FREC), Fundani Centre for Higher Education Development, Cape Peninsula University of Technology, FREC:REF: 23/19.

Results of the critical review: How laboratories shape engineering identities

The theoretical framework identified five dimensions of identity formation: temporal, spatial, material, performative and discursive; these categories were used to structure the findings of the review.

Past, present and future: Co-temporal identities in the engineering laboratory

Of the 57 studies, eight (14%) emphasised temporality, showing how students' engineering identities changed over the course of an engineering programme. Several studies

discussed issues of orientation and induction into laboratory practices, as well as students' future aspirations and how these laid the foundation of an engineering identity.^{12,17} Studies found that involving first-year students in engineering communities was key to early identification with engineering. For example, 'vertical mentoring', a process whereby more senior students provided 'laboratory tours and technique training, and social events',¹⁸ was found to be effective for early identification with engineering, whilst collaboration with more senior students on laboratory projects was associated with commitment to an engineering career.^{26,31} Conversely, students' inability to relate to the engineering profession and take on an emerging professional identity over time was exacerbated when there was a lack of interaction between novice and senior students.³²

The presence of students at different levels in engineering laboratories was important in inducting students into laboratory spaces and practices. First-year students viewed more senior students in the laboratory as peer role models, repositories of engineering knowledge and usually more approachable than lecturers.³¹ In bioengineering, 'building' was a common activity that inducted new students into laboratory practices, affording 'new students with opportunities for rapid participation and the build-up of requisite knowledge'.²⁷ Senior students provided access to research experience, mentoring and involvement in an engineering community.³³

The studies noted a gap between engineering students' expectations about what an engineering course might involve and the actual subjects taught. Studies noted that students had idealised understandings of the everyday work of a professional engineer and thus needed support 'to make sense of what they meet'.³⁴ The temporary deferment of a professional identity is not uncommon in professional programmes; students' engineering identities are future projections that relate to potential jobs.¹² The difficulty for many engineering students was that the construction of an engineering identity could be:

[A] vulnerable process whereby students, even if they join the programme, determined to complete it, experience difficulties in constructing a viable narrative and therefore often need to consider leaving the course.^{34(p. 784)}

When students felt isolated from each other, from their teachers and the greater engineering community, they were unlikely to develop an engineering identity over time.³¹

The literature reported on a range of pedagogical practices that were shown to strengthen emerging engineering identities by accommodating both beginners and more experienced students and researchers in laboratories to establish a supportive engineering community within a department or faculty,³² promoting teamwork to fast-track skills and knowledge³³ and linking laboratory practices to engineering career paths.¹⁷

Spatial affordances for the development of engineering identities

Sixteen of the studies (28%) addressed spatio-cultural dimensions of identity formation in the laboratory. A key aspect of laboratories is their affordance for engaged learning, through dedicated social spaces where laboratory teams can interact, both formally and informally.⁶ Engineering laboratories, by their nature, are spaces for experimenting, discovery and meaning-making, thus tending to embody active learning pedagogical principles. Enabling students' access to particular laboratories had 'an influence on identity development by allowing the students to recognise their admission to a specific community'.¹⁹ The positive contribution of active learning in laboratories to engaging students' interest in engineering subject matter and in identity formation was recognised in a number of studies,^{7,18} but many studies also pointed to negative experiences in engineering laboratories. Women students and underrepresented groups described themselves as 'isolated',¹⁴ 'side-lined'³⁵ or 'not participating fully'.⁴ Students who came into engineering laboratories without previous experience or knowledge of engineering laboratories often struggled to gain acceptance.³ Invisibility, isolation, misrecognition and marginalisation were common themes in the literature on engineering identity.^{1,5,21,22}

Shifting from physical to virtual engineering laboratories impacted emergent engineering identities. Tibbits and colleagues pointed out that 'innovative learning spaces can influence the norms of long-established disciplines'⁶; in this sense, the virtual laboratory was found to be a more inclusive space for rehearsing an engineering identity. In the virtual laboratory, students were able to immerse themselves in laboratory-based learning, provided that the virtual laboratory afforded an appropriate 'presence', that is, the extent to which students felt that they were physically present in the virtual laboratory. 'Hands-on' work in laboratories is increasingly replaced by 'mouse-pointer-on' work,¹³ and the literature suggests that there is little difference in learning outcomes whether students engage in physical or virtual laboratories.^{11,13} In several cases, virtual laboratories were shown to be more effective for immersing students in engineering studies than physical laboratories.^{11,36} This was particularly the case when assistive technologies were available to students with disabilities.^{37,38} When gaming was used as a laboratory simulation (and defence games in particular), students were provided with 'multiple ways to engage in the classroom and contribute whilst promoting their critical thinking and collaboration skills, encouraging consistent student participation throughout the semester'.³⁹ The use of narrative and character creation enhanced students' identification with engineering by making them feel that their engineering abilities could influence social or environmental outcomes.

Even where physical engineering laboratories remain an integral part of the engineering curriculum, many laboratory

activities have been adapted for virtual tools.⁴⁰ In this regard, a number of studies argued that augmenting engineering laboratories with a wide variety of virtual technologies closely simulated industry laboratories and supported identification with the engineering profession.¹² Augmented laboratories could respond more quickly to changes in the real world, enabling engineering programmes to react to new trends and face changes caused by new technologies, changing industry needs and new educational paradigms.¹³ Engineers 'investigate real-world phenomena through simulation models, physical or computational',⁴¹ and the use of virtual tools in a physical space supported this identification.

The laboratory space is often extended into field testing under conditions that are more authentic to real-world engineering contexts. Field testing that emphasised 'iterative socio-technical design' had the potential to change engineering identities, enabling students to see themselves 'as responsible agents who react to possibilities, who shape new technology ... and who themselves are continually experiencing, negotiating and developing'.⁴² Field testing implied a shift to sustainable forms of engineering that required a broadening of the engineering identity.⁴³ Anchoring laboratory experiments in 'realistic challenges' was found to enable students to understand the practical applications of concepts and principles covered in different laboratory practicals.¹⁸ Marshall and colleagues highlight 'the critical element of authenticity'⁴⁴ in engineering identity formation. Thus, laboratory projects that were aligned to appropriate industry projects were valuable in promoting a professional identity.

Social interactions in the laboratory impact the kind of engineers that students will become; thus, laboratory pedagogies should be attentive to how negative cultures might be reproduced.⁵ The literature provided many examples of how pedagogies that facilitated experimental discovery and active engagement and were authentic enabled the emergence of diverse engineering identities.⁴⁵

Materialising an engineering identity with artefacts and tools

Twelve studies on engineering tools and artefacts (22%) proposed that the materiality of the engineering laboratory was central to cultivating a professional identity. Many initial experiences in the laboratory developed around mentoring newcomers in the use of the tools, artefacts and devices that were key to engineering work.^{41,46} In her ethnographic research in biomedical engineering laboratories, Nersessian found that professional identities were, in part, created through 'person-to-artefact cognitive partnering'.⁴¹ Engaging with engineering tools, such as 'building a robot from start to finish [*was*] an intensely engrossing experience that motivate[d] the students to learn about many of the less glamorous theoretical aspects [*of engineering*]'.⁴⁷ As an engineering identity matured, laboratory artefacts came to represent familiar and trusted methods.

Specialised engineering laboratories contained what Nersessian called 'signature artifacts',⁴¹ that is, specialised laboratory tools that further defined an engineering identity. Specialisation in engineering was associated with the proficient use of specialised tools⁴⁸ and engineering students tended to identify more closely with specialised tools as they progress in their studies. In an electrical engineering context, for example, students self-identified as 'analog guys' or 'digital guys'⁴⁹ as they began to specialise in their discipline.

Interdisciplinary awareness, in particular, understanding the links between the science subjects that underpinned engineering disciplines and real-world problem-solving, was particularly important in enabling students to identify the presence of mathematical tools in real-world problem-solving: 'this recognition encourage[d] the development of identity as a novice engineer'.⁹ As students gained greater proficiency in the application of specialised tools, they were better able to contribute to interdisciplinary teams, which strengthened their professional identities as they gained insights into engineers' contributions towards solving complex problems.⁵⁰

Several research studies suggested that generic engineering tools,⁴⁶ a 'makerspace'⁵⁰ or a 'student managed Sandbox',⁴⁵ were effective in enabling an innovative engineering identity. Morocz and colleagues⁴⁶ argued that in order to express an engineering identity, students needed to:

[S]imply mess about with, design-build projects, tools, materials, and mentoring within a community of their own management, independent of curricular requirements, classroom projects, or hierarchical structure of coursework.^{46(p. 3)}

In this study, students were provided with '3D printers, laser cutters, waterjet cutter, injection moulding, thermoforming, milling and others, along with lounge, meeting, assembly and testing space'.⁴⁶ Providing students with free access to hands-on state-of-the-art technologies, encouraging collaboration between diverse teams of students from all years and majors and welcoming all types of projects excited students and strengthened their identities as future engineers. When resources were more constrained, virtual laboratories could similarly provide innovative and authentic engineering tasks and tools.¹¹ As engineering students advanced in their studies, they valued laboratories as dedicated spaces in which to work on design projects.²⁰

Recommended pedagogies included drawing on undergraduate students' fascination with materiality to familiarise students with the engineering tools of their disciplines and building on this interest to engage students more deeply with engineering tools and devices. Socio-material relations in engineering laboratories were found to be complex and evolving. The challenge was to select appropriate forms of mentoring students towards understanding and using appropriate laboratory equipment at different levels of study.²⁰

Performing engineering: Developing competence in the laboratory

Fifteen studies (26%) foregrounded the importance of competence, particularly in experimentation, problem-solving and design, for engineering identity formation.^{32,33} As students engaged in laboratory work, over time, they learned 'to participate in the practices of the community they have entered'.⁵¹ 'Belonging' in engineering required students to acquire the necessary skills and competence required for their field, which usually combined 'problem-solving, people skills and technical skills'.¹³ Without competence in laboratory work, students were likely to become 'isolated, overlooked and unheard'.¹⁴

Undergraduate students' participation in research projects involving senior or postgraduate students built a laboratory-based community of practice that enabled them to become 'active participants in the construction of both knowledge and community in engineering labs'.²⁸ Undergraduate research experiences were important for 'how students develop a researcher identity and transform their epistemic beliefs'.³³ Studies noted an improvement in retention when undergraduates were provided with immersive research experiences³² or 'challenge-inspired undergraduate experiences'.¹⁸ In general, the more 'structured problem sets', typical of early laboratory practicals, became more 'open-ended problems' in advanced laboratory work.¹⁹ Authenticity and a 'realistic local context' supported emerging engineering identities.⁴⁴

The literature suggests that students more clearly take on engineering identities in design laboratories.^{8,10} Predominantly, it was students' performance in the laboratory that showed whether or not they were engineers.⁴⁵ In the study by Beaudoin and Llis, for example, teams of two or three first-year engineering students explored engineered products or processes 'by playing the successive roles of user, assembler, and engineering analyst'.⁸ The role-play format provided a hands-on, collaborative learning environment to improve students' manipulative, problem-solving and creative thinking skills, thus promoting an early identification with engineering.

Performance and roles in the laboratory are particularly susceptible to the reproduction of stereotypes. A difficulty in laboratory group work was found in how roles were allocated to group members, based on gender, social, or academic group stereotyping. For example, female students tended to assume more organisational roles, attributed to women's better organisational skills.¹⁴ As a result of gendered roles in group work, women students participated less and lost confidence in comparison with male students who appeared to be confident and competent.¹⁵ In his study, Johri emphasised the socio-material nature of laboratory demonstrations ('demos'). He defined 'demos' as:

[P]erformances wherein the product had a major role and was presented to the audience with a specific purpose in mind ... [using] the right mix of verbal, visual, and interactive elements to persuade the audience of the value of the designed artifact.^{51(p.7)}

Evaluating laboratory performance is important in identity building and is one of the main ways in which engineering educators can affirm or deny a student's emerging engineering identity. Marshall and colleagues argued that the full range of laboratory performance, including 'research skills, conceptual understanding, application of techniques, preparing a report, team working abilities and the communication skills needed to interact with peers and demonstrators effectively'⁴⁴ could not be adequately assessed through traditional engineering reports; thus, more innovation methods were required. Naim and colleagues similarly argued that laboratory assessment should include 'cognition, psychomotor and affective domains of knowledge'⁴⁸ and that paying attention to ethics in the laboratory was important for constructing strong professional identities.

Creative thinking and innovation are at the heart of engineering problem-solving and design and the literature shows the importance of innovative pedagogies and assessment approaches in support of this. Developing professional skills alongside technical knowledge in engineering performance was found to be important in supporting emerging engineering identities. Laboratory pedagogies that represented the engineering profession, such as problem-based learning, were more likely to support students' emerging identities than 'traditional version[s]' of laboratory instruction.⁴⁴ Innovative forms of assessment, such as portfolio assessment, were aligned to professional skills and the dual nature of engineering identity – both recognising oneself as an engineer and receiving recognition from the engineering community. The literature warns that a lack of full participation in undergraduate laboratory experiences can 'chip away'⁴³ at students' identity, ultimately pushing students out of engineering.

Communicating engineering identities: Discursive practices in the laboratory

Six studies (10%) showed how discursive elements impact emerging identities. Discursive elements of identity formation were found to be related both to the messages that students received in the communication of others⁴ and their growing mastery of technical discourse.⁴⁹ Students were strongly attuned to the messages that they received about what counts as engineering and what makes an engineer.⁵²

Technical communication, such as laboratory reporting, was more effectively acquired in the laboratory than formally taught in communication courses.⁵² Setting written assignments that were integrated into core engineering courses signalled to students that writing mattered in engineering. When engineering students worked with both communication and engineering lecturers, their motivation and identification with engineering increased.⁵² Embedding the process of writing in a laboratory setting provided a structured opportunity for students to review their own and others' work critically, thus being guided towards improving their technical writing.⁵³ Jocuns and Stevens proposed a 'trajectory of identification' in the ability of engineering students to 'talk

engineering',⁴⁹ arguing that spoken technical communication was a significant part of the development of an engineering student's identity. Presentation skills, particularly in laboratory demonstrations, were identified as a key oral communication genre in engineering, entailing the development of a 'socio-scientific argumentation [that] includes the application of moral and ethical values and personal identity'.⁵⁴

Whilst reporting and other forms of technical communication imply communication within an engineering community, 'translation' refers to communicating engineering to non-specialist audiences, including interdisciplinary and interprofessional forms of communication.⁵⁵ Translating required students to define the nature of the audience for effective communication with non-engineering or interprofessional collaborators.⁵⁵

Collegial discourse styles influenced undergraduates' sense of belonging. As a powerful tool of socialisation, engineering 'disaster stories' contain messages of self-deprecation, humility, teamwork and mutual learning.²⁸ They offered novices the opportunity to learn from more experienced engineers' errors. Disaster stories reduced the hierarchy, normalised learning through mistakes and built relationships amongst undergraduates and more experienced students and

academics. It was found that engineering narratives had the potential 'to promote collaboration, a sense of belonging, and the value of continuous learning for all lab members', whilst also addressing students' perceptions that engineering studies have a 'lack of real-world application and lack of meaning'.³

Synthesis

The findings of the critical review with regard to the temporal, spatial, material, performative and discursive elements in engineering identity formation, the ways in which the literature expanded and developed these categories in the laboratory context and the ways in which the emerging identities were affirmed and supported by appropriate laboratory pedagogies are synthesised in Table 2.

Table 2 shows that by contextualising identity formation within the engineering laboratory, the critical review was able to provide depth and detail to the fundamentals of time, space, material, performance and discourse. The theoretical framework that guided the study was consequently expanded, providing subcategories of each dimension: orientation, inclusion, induction and aspiration in the temporal dimension; engagement, modelling, simulation and field testing in the

TABLE 2: Synthesis of results: The impact of laboratory spaces and practices on emergent engineering identities.

Dimensions of identity	Activities in engineering laboratories need to...	Laboratory affordances	Signature laboratory pedagogies that support identity formation	References
Temporal	... affirm students' prior identities in an engineering environment	Orientation	'Tiered mentoring' orientation in which senior, demographically diverse, students orient first-year students	2, 12
	... cultivate a sense of belonging in engineering	Inclusion	Collaboration between students at all levels on research and design	26
	... promote early identification with engineering	Induction	Encourage role play in the laboratory (e.g. user, assembler and analyst); avoid stereotypes in role allocation	17, 31
	... shape students' aspirations towards a future engineering identity	Aspiration	Simulated workplace projects and the inclusion of workplace collaborators and/or assessors	34, 37
Spatial	... facilitate students' diverse learning styles and abilities	Engagement	Laboratories can support diverse learning styles and disabilities	2, 9, 14
	... engage students in engineering problem-solving and design	Modelling	Spaces that promote interactions with 'fellow students, teachers and industry' are key to identity formation	5, 6, 7, 10
	... introduce students to modelling techniques	Simulation	Blended laboratories should support investigation into real-world phenomena through simulation models	11, 13, 36
	... extend to 'real-world' social contexts beyond the laboratory	Field testing	The 'ecological, social and technical' become interconnected in field testing	40, 42, 43
Material	... introduce students to basic engineering tools	Familiarisation	'Person-to-artefact cognitive partnering' in which engineering tools represent familiar and trusted processes over time	27, 41, 49
	... introduce students to specialised engineering tools	Specialisation	Mastery of specialised tools (and their socio-material affordances) is key to a specialised engineering identity	10, 45, 47
	... encourage students to apply tools to social/ environmental problems	Contribution	Interdisciplinary projects/ teamwork (e.g. with medical students) support emerging engineering identities	50
	... support innovative problem-solving and design	Innovation	Generic laboratories, beyond the basic 'cognition, psychomotor and affective domains' enable creativity	46
Performative	... introduce students to engineering problem-solving and research processes and methods	Experimenting/ problem-solving	Early undergraduate research experiences support an emerging engineering identity	28, 33
	... enable students to become designers	Design	Design challenges enable emerging engineering identities without sacrificing existing identities	18, 35
	... enable others to affirm students' engineering identity/ performance	Demonstration	Structures and practices to support multiple/critical engineering agencies	4, 8, 15, 19, 51
	... help students to assess their engineering identity/ performance	Assessment	In-class assessment and conventional report-based assessment for optimal laboratory learning	44, 48
Discursive	... encourage intraprofessional communication	Narrating	Telling engineering 'disaster stories' (and other engineering narratives) is inclusive and affirming	39
	... encourage interprofessional communication	Reporting	Technical communication is best learned in an engineering laboratory	52, 53
	... provide opportunities for extraprofessional communication	Translating	Being able to communicate engineering to non-engineers (and influence of public perceptions)	55
	... encourage collegial, inclusive communication practices	Presenting	Competence in presenting and arguing on a scientific basis	54

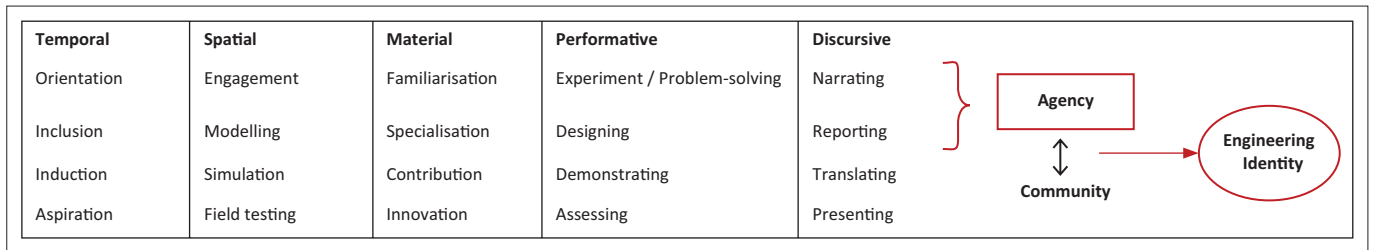


FIGURE 3: Dimensions of identity formation in engineering laboratories.

spatial dimension; familiarisation, specialisation, contribution and innovation in the material dimension; experimenting, problem-solving, designing, demonstrating and assessment in the performative dimension and narrating, reporting, translating and presenting in the discursive dimension.

Figure 3 shows how the findings of the critical review expanded the theoretical framework (Figure 1) to create a more detailed and contextualised understanding of the elements of identity formation in engineering education.

Conclusion

This critical review of the literature analysed the impact that engineering laboratories have on emerging professional identities across a range of engineering disciplines and fields. The analysis appropriated the lens of 'ontological formation'^{23,24,25} to understand how engineering identities were enabled or constrained by laboratory spaces and practices. Whilst there are many studies of engineering identity, including systematic reviews of the literature,^{1,21,22} the contribution to knowledge that this critical review offers is a synthesis of relevant studies through a focus on identity formation in the engineering laboratory that shows the connection between categories of identity formation and supportive laboratory pedagogies.

Implications for practice: Pedagogies for identity formation

Recommendations for identity-affirming pedagogical interventions arise from the results of the critical review and are based on a theorised understanding of engineering identity formation. The critical review of the literature proposes pedagogical changes that better align education interventions with the dimensions of engineering identity, including effective practices for orientation, inclusion, induction and so on. The literature points to a number of 'critical incidents' that strengthen the engineering identity, such as peer-mentoring, building multi-generational laboratory communities, undertaking undergraduate research projects, authentic problems and industry linkages, field testing beyond the laboratory, demonstrating and assessing competent performance and many others. Similar identity-building pedagogies could intentionally be infused into the design of undergraduate laboratory programmes in order to support the early emergence of an engineering identity and enhance retention across engineering programmes.

Implications for further research: Developing the identity formation framework

This critical review pointed to the need for future research to advance our understanding of how engineering identities are formed, such as using the identity formation framework to implement a laboratory programme and empirically study its impact and testing the ontological formation model in other learning contexts, for example, in the classroom-based teaching of engineering sciences. As we advance in our understanding of how students identify with engineering and how students receive external recognition of their engineering identity, more students, and particularly students from under-represented groups, are likely to be retained in engineering programmes and the engineering profession.

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Authors' contributions

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Data availability

The database for the critical review of the literature is available from the CPUT library's open data repository <https://www.cput.ac.za/lib/>.

Disclaimer

The views and opinions expressed in this article are those of the authors and do not necessarily reflect the official policy or position of any affiliated agency of the authors.

References

- Patrick AD, Borrego M. A review of the literature relevant to engineering identity. Paper presented at: ASEE 2016. Proceedings of the 123rd ASEE Annual Conference & Expo; 2016 Jun 26–29; New Orleans, LA: American Society for Engineering Education. Paper ID: 15028.
- Malone KR, Barabino G. Narrations of race in STEM research settings: Identity formation and its discontents. *Sci Educ.* 2009;93(3):485–510. <https://doi.org/10.1002/sce.20307>
- Godwin A, Potvin G. Pushing and pulling Sara: A case study of the contrasting influences of high school and university experiences on engineering agency, identity, and participation. *Res Sci Teach.* 2017;54(4):439–462. <https://doi.org/10.1002/tea.21372>
- Secules S, Gupta A, Elby A, Turpen CA. ‘Turning Away’ from an undergraduate programming student: Revealing culture in the construction of engineering ability. Paper presented at: AERA 2016. Proceedings of the American Educational Research Association Annual Meeting; 2016 Apr 8–12; Washington, DC: American Educational Research Association. Paper ID: 301302074.
- Tonso KL. Student engineers and engineer identity: Campus engineer identities as figured world. *Cult Stud Sci Educ.* 2006;1(2):273–307. <https://doi.org/10.1007/s11422-005-9009-2>
- Tibbits G, Jolly L, Szymakowski J, Maynard N, Tade MO. The engineering pavilion – A learning space developing engineers for the global community. Paper presented at: ICL 2014. Proceedings of the IEEE International Conference on Interactive Collaborative Learning; 2014 Dec 3–6; Dubai, Emirates: Institute for Electrical and Electronic Engineering. p. 106–111.
- Moozeh K, Farmer J, Tihanyi D, Nadar T, Evans GJ. A prelaboratory framework toward integrating theory and utility value with laboratories: Student perceptions on learning and motivation. *J Chem Educ.* 2019;96(8):1548–1557. <https://doi.org/10.1021/acs.jchemed.9b00107>
- Beaudoin DL, Llis DFO. A product and process engineering laboratory for freshmen. *J Eng Educ.* 1995;84(3):279–284.
- Craig TS. Development of an engineering identity: Personal discovery of classroom mathematics in ‘real engineering’. *Afr J Res Math Sci Technol Educ.* 2010;4(2):56–70. <https://doi.org/10.1080/10288457.2010.10740682>
- Watkins SE. An engineering physics introduction to electronics for ECE sophomores. Paper presented at: ASEE 2013. Proceedings of the 120th ASEE Annual Conference and Exposition; 2013 Jun 23–26; Atlanta, GA: American Society for Engineering Education. Paper ID: M661.
- Koretsky M, Kelly C, Gummer E. Student perceptions of learning in the laboratory: Comparison of industrially situated virtual laboratories to capstone physical laboratories. *J Eng Educ.* 2011;100(3):540–573. <https://doi.org/10.1002/j.2168-9830.2011.tb00026.x>
- Kapoor A, Gardner-McCune C. Understanding professional identities and goals of computer science undergraduate students. Paper presented at: SIGCSE 2018. Proceedings of 49th ACM Technical Symposium on Computer Science Education; 2018 Feb 21–24; Baltimore, MA: American Computing Machines. p. 191–196.
- Gustavsson I, Nilsson K, Zackrisson J, et al. On objectives of instructional laboratories, individual assessment, and use of collaborative remote laboratories. *IEEE Trans Learn Tech.* 2009;2(4):263–274. <https://doi.org/10.1109/TLT.2009.42>
- Ayre M, Mills J, Gill J. ‘Yes, I do belong’: The women who stay in engineering. *Eng Stud.* 2013;5(3):216–232. <https://doi.org/10.1080/19378629.2013.855781>
- Hosaka M. Women’s experiences in the engineering laboratory in Japan. *Eur J Eng Educ.* 2014;39(4):424–431. <https://doi.org/10.1080/03043797.2014.883363>
- Feisel LD, Rosa AJ. The role of the laboratory in undergraduate engineering education. *J Eng Educ.* 2005;94(1):121–130.
- McCartney R, Sanders K. School/work: Development of computing students’ professional identity at university. Paper presented at: ICER 2015. Proceedings of the 11th annual ACM International Conference on International Computing Education Research; 2015 Aug 9–13; Omaha, NE: American Computing Machines. p. 151–159.
- Pool M, Bhargava R, Carney PS, Pan D, Smith AM. Implementing a challenge-inspired undergraduate experience. Paper presented at: ASEE 2016. Proceedings of the 123rd ASEE Annual Conference & Expo; 2016 Jun 26–29; New Orleans, LA: American Society for Engineering Education. Paper ID: 16477.
- Stevens R, O’Connor K, Garrison L, Jocuns A, Amos DM. Becoming an engineer: Toward a three dimensional view of engineering learning. *J Eng Educ.* 2008;97(3):355–368. <https://doi.org/10.1002/j.2168-9830.2008.tb00984.x>
- Mahmud MN, Abdul WM, Jiashen T, Isa NA. Sustaining learning in engineering capstone design using sociomaterial approaches. Paper presented at: WEEF 2017. Proceedings of the 7th IEEE World Engineering Education Forum; 2017 Nov 13–16; Kuala Lumpur, Malaysia: Institute for Electrical and Electronic Engineering. p. 812–817.
- Morelock JR. A systematic literature review of engineering identity: Definitions, factors, and interventions affecting development, and means of measurement. *Eur J Eng Educ.* 2017;42(6):1240–1262. <https://doi.org/10.1080/03043797.2017.1287664>
- Rodriguez SL, Lu C, Bartlett M. Engineering identity development: A review of the higher education literature. *Int J Educ Math Sci Technol.* 2018;6(3):254–265.
- Barad K. Posthumanist performativity: Toward an understanding of how matter comes to matter. *Signs: J Wom Cul Soc.* 2003;28(3):801–831. <https://doi.org/10.1086/345321>
- James P. Urban design for the global south: Ontological design in practice. In: Kalantidou E, Fry T. editors. *Design in the Borderlands*. London: Routledge, 2014; p. 101–118.
- Pickering A. The ontological turn: Taking different worlds seriously. *Soc Anal.* 2017;61(2):134–150. <https://doi.org/10.3167/sa.2017.610209>
- Butterfield A, Branch KJ. Collaboration between seniors and freshmen on senior capstone projects. Paper presented at: ASEE 2016. Proceedings of the 123rd ASEE Annual Conference & Expo; 2016 Jun 26–29; New Orleans, LA: American Society for Engineering Education. Paper ID: 15618.
- Newstetter WC, Behraves E, Nersessian NJ, Fasse BB. Design principles for problem-driven learning laboratories in biomedical engineering education. *Ann Biomed Eng.* 2010;38(10):3257–3267. <https://doi.org/10.1007/s10439-010-0063-x>
- Wylie CD, Gorman ME. Learning in laboratories: How undergraduates participate in engineering research. Paper presented at: ASEE 2018. Proceedings of the 125th ASEE Annual Conference & Expo; 2018 Jun 24–27; Salt Lake City, UT: American Society for Engineering Education. Paper ID: 22448.
- Evans N, Bausewein C, Meñaca A, et al. A critical review of advance directives in Germany: Attitudes, use and healthcare professionals’ compliance. *Pat Educ Counsel.* 2012;87(3):277–288. <https://doi.org/10.1016/j.pec.2011.10.004>
- Eva KW. On the limits of systematicity. *Med Educ.* 2008;42(9):852–853. <https://doi.org/10.1111/j.1365-2923.2008.03140.x>
- Crenshaw TL, Metcalf H, Chambers EW, Thakkar U. A case study of retention practices at the University of Illinois at Urbana-Champaign. Paper presented at: SIGCSE 2008. Proceedings of 39th ACM Technical Symposium on Computer Science Education; 2008 Mar 12–15; Portland, OR: American Computing Machines. p. 412–416.
- Dahlberg T, Barnes T, Rorrer A, Powell E, Cairco L. Improving retention and graduate recruitment through immersive research experiences for undergraduates. Paper presented at: SIGCSE 2008. Proceedings of 39th ACM Technical Symposium on Computer Science Education; 2008 Mar 12–15; Portland, OR: American Computing Machines. p. 466–470.
- Benson LC, Kennedy MS, Ehlert KM, et al. Understanding undergraduate engineering researchers and how they learn. Paper presented at: FIE 2016. Proceedings of the IEEE Frontiers in Education Conference; 2016 Oct 12–15; Erie, PA: Institute of Electrical and Electronic Engineering. Paper ID: 16505087.
- Holmegaard HT, Madsen LM, Ulriksen L. A journey of negotiation and belonging: Understanding students’ transitions to science and engineering in higher education. *Cult Stud Sci Educ.* 2013;9:755–786. <https://doi.org/10.1007/s11422-013-9542-3>
- Nisbet J, Haw MD, Boon S, Harrington RW, Fletcher AJ. Group work experiences of women students in a Scottish chemical engineering programme. *Educ Chem Eng.* 2016;16:39–47. <https://doi.org/10.1016/j.ece.2016.07.002>
- Vial PJ, Nikolic S, Ros M, Stirling D, Doulai P. Using online and multimedia resources to enhance the student learning experience in a telecommunications laboratory within an Australian university. *Australas J Eng Educ.* 2015;20(1):71–80.
- Grout I. Remote laboratories as a means to widen participation in STEM education. *Educ Sci.* 2017;7(4):85–92. <https://doi.org/10.3390/educsci7040085>
- Jenson R, Petri A, Day A, Truman K, Duffy K. Perceptions of self-efficacy among STEM students with disabilities. *J Postsecond Educ Disabil.* 2011;24(4):269–283.
- Anastasio DD, Suresh A, Burkey DD. Impact of narrative, character creation, and game mechanics on student engagement in a game-based chemical engineering laboratory course. Paper presented at: ASEE 2015. Proceedings of the ASEE 122nd Annual Conference and Expo; 2015 Jun 14–17; Seattle, WA: American Society for Engineering Education. Paper ID:12396.
- Mhiri R, Besbes M, Saad M, Nerguizian V, Ben Attia H. Implementation of Laboratory at Distance (LAD): Specific considerations and recommendations. Paper presented at: ICELIE 2013. Proceedings of the 7th IEEE International Conference on e-Learning in Industrial Electronics; 2013 Nov 10–13; Vienna, Austria: Institute for Electrical and Electronic Engineering. p. 52–56.
- Nersessian NJ. How do engineering scientists think? Model-based simulation in biomedical engineering research laboratories. *Top Cogn Sci.* 2009;1(4):730–757. <https://doi.org/10.1111/j.1756-8765.2009.01032.x>
- Carroll JM, Rosson MB. Wild at home: The neighborhood as a living laboratory for HCI. *ACM Trans Comp-Hum Int.* 2013;20(3):1–28.
- Date G, Chandrasekharan S. Beyond efficiency: Engineering for sustainability requires solving for pattern. *Eng Stud.* 2018;10(1):12–37. <https://doi.org/10.1080/19378629.2017.1410160>
- Marshall J, Bhasin A, Boyles S, David B, James R, Patrick A. A project-based cornerstone course in civil engineering: Student perceptions and identity development. *Adv Eng Educ.* 2018;6(3):1–25.
- Romney GW, Stevenson BR. An isolated, multi-platform network Sandbox for teaching IT security system engineers. Paper presented at: SIGITE 2004. Proceedings of the 5th ACM Conference on Information Technology Education; 2004 Oct 28–30; Salt Lake City, UT. p. 19–23.
- Morocz R, Levy B, Forest C, et al. University maker spaces: Discovery, optimization and measurement of impacts. Paper presented at: ASEE 2015. Proceedings of 122nd Annual Conference & Expo; 2015 Jun 14–17; Seattle, WA: American Society for Engineering Education. Paper ID: 11931.
- Kumar D, Meeden L. Robot laboratory for teaching artificial intelligence. *ACM SIGCSE Bul.* 1998;30(1):341–344. <https://doi.org/10.1145/274790.274326>

48. Naim NF, Hashim H, Latip MFA, Abidin HZ, Samin SS. OBE performance evaluation tool for electrical engineering laboratory. Paper presented at: ICNIT 2010. Proceedings of the IEEE International Conference on Networking and Information Technology; 2010 Jun 11–12; Manila, Philippines: Institute for Electrical and Electronic Engineering. p. 200–204.
49. Jocuns A, Stevens R. 'Current is the one that's mean': The development of engineering student trajectories of identification. In: Kanselaar, G, Jonker, V, Kirschner, PA, Prins, FJ, editors. International perspectives in the learning sciences: Creating a learning world. Proceedings of the Eighth International Conference for the Learning Sciences – ICLS 2008, Volumes 3. 2008 Jun 24–25; Utrecht, The Netherlands: International Society of the Learning Sciences, p. 49–50.
50. Ludwig PM, Nagel JK, Lewis EJ. Student learning outcomes from a pilot medical innovations course with nursing, engineering, and biology undergraduate students. *Int J STEM Educ.* 2017;4(1):33. <https://doi.org/10.1186/s40594-017-0095-y>
51. Johri A. Learning to demo: The sociomateriality of newcomer participation in engineering research practices. *Eng Stud.* 2012;4(3):249–269. <https://doi.org/10.1080/19378629.2012.709520>
52. Cook K, Jacob R. Where language and engineering meet: Fostering emerging engineering identities among international English language learners. Proceedings of the Canadian Engineering Education Association (CEEA); 2018 Jun 4–7; Toronto: Canadian Engineering Educational Association. Paper ID: 9483.
53. Hubka CA, Chi E, Chen Y, et al. A writing in the disciplines approach to technical report writing in chemical engineering laboratory courses. Paper presented at: ASEE 2019. Proceedings of the ASEE 126th Annual Conference & Expo; 2019 Jun 16–19; Tampa, FL: American Society for Engineering Education. Paper ID: 25222.
54. Grooms J, Sampson V, Golden B. Comparing the effectiveness of verification and inquiry laboratories in supporting undergraduate science students in constructing arguments around socioscientific issues. *Int J Sci Educ.* 2014;36(9):1412–1433. <https://doi.org/10.1080/09500693.2014.891160>
55. Wagner EL, Newell S, Ramiller N, Enders J. From public ideology to socio-material reproduction of agile principles: The case of pivotal labs. *Inf Organ.* 2018;28(4):192–210. <https://doi.org/10.1016/j.infoandorg.2018.10.002>