1 Introduction

The pedagogical practice of group work has a long history in higher education, having been the subject of formal research in the field for over a century (Johnson et al., 1998). Despite this, tension persists between different educational approaches in engineering, specifically between traditional lectures with accompanying homework, problem sets, and exams, and active learning approaches such as collaborative and cooperative learning (Bubou et al., 2017; Wieman, 2014). Collaborative learning is an active learning approach that more closely resembles the practices of engineering professionals in industry settings than traditional educational techniques (Cady & Reid, 2018; Prince, 2004). Because working effectively on a team is crucial to success in the engineering workplace (Johri et al., 2015; Jonassen et al., 2006), engineering accreditation agencies worldwide specify it as an explicit learning outcome (e.g., ABET Accreditation Board for Engineering and Technology, Criteria for Accrediting Engineering Programs, 2018).

Research in the learning sciences has demonstrated that collaborative, problem-based, and design-focused experiences produce deep learning, increase persistence in STEM fields, and aid the development of the collaborative skills that are essential for industry (e.g., Barron & Darling – Hammond, 2008; Nokes – Malach et al., 2019). As Sheppard et al. suggest in Educating Engineers (Sheppard & Macatangay, 2008), these best practices for developing effective learning opportunities should be adopted across engineering programs in order to prepare budding engineers to collaboratively address multidisciplinary and complex problems in their professional careers.

This chapter brings together research on collaborative and cooperative learning in education, the learning sciences, and engineering education. Our goal is to review current understandings of the purposes of collaborative learning, how collaboration leads to learning, and the conditions necessary to have successful collaborative learning experiences in engineering courses. The chapter is written both as a guide for how to think about implementing collaborative learning and to prepare the ground for future research in the field.

While the concept of active learning encompasses a large range of activities, we have limited our focus to learning activities that take place in groups where there is some sustained interaction between group members – from at least one class period or lesson to semester-long team projects. We also acknowledge a significant, if possibly temporary, increase in the use of online learning and group work during recent years. However, the scope of this chapter does not allow us to include...
a detailed examination of the emerging literature on sustaining collaboration solely in an online context.

We use the 4Ts framework developed by the first author (Mercier & Higgins, 2015) to outline the crucial elements of collaborative learning in classrooms: teams, tasks, tools, and teachers. These four categories are useful in mapping the current state of the field and identifying areas in which further research is necessary. While laying out these categories, however, this framework also acknowledges their fundamentally overlapping nature (e.g., team interaction is influenced by the type of task being used, and so on).

We reviewed papers published between 2010 and 2022 in the European Journal of Engineering Education, the International Journal of Engineering Education, the Journal of Engineering Education, and Studies in Engineering Education. We arrived at this short list by seeking to represent the “top” journals in standard engineering education research using a combination of impact factor, h-index, and indexing databases while representing a variety of countries. We identified papers using the following keywords: collaborative learning, cooperative learning, group work, capstone project, group-based, and design project. We then categorized these papers using the 4Ts framework to provide insights into the current state of the field, explore implications for teaching, and highlight directions for future research.

2 Overview of Collaborative Learning

2.1 Collaborative and Cooperative Learning

The terms “collaborative learning” and “cooperative learning” are often used interchangeably (Hmelo-Silver et al., 2013), with early studies in engineering education preferring the latter term (Froyd et al., 2012; Smith et al., 1981a, 1981b). In this chapter, we will draw a distinction between the terms in order to clarify different aspects of these processes, recognizing that elements of both types of learning are necessary in engineering education and that the differences between them are neither entirely clear nor universally agreed upon in the field.

Smith et al. (2005) use the requirement in cooperative learning of structured, individual accountability to disambiguate from cooperative and collaborative learning. Alternatively, Dillenbourg et al. (1995) define the key feature of cooperative learning as individuals having responsibility for different elements of the task, while collaborative learning is defined as a high level of mutual engagement and coordinated effort to solve the problem or create joint understanding. Drawing on this literature, we define collaborative learning as requiring the co-construction of knowledge by groups. Cooperative learning, on the other hand, is defined as groups interdependently working to achieve a common goal, which results in activities that lend themselves to students taking different roles during a task, and possibly breaking the task down into subparts and completing them under a rubric of individual accountability (Davidson & Major, 2014; Smith et al., 2005). While this chapter is focused on collaborative learning, it should be noted that there is significant overlap in these two forms of pedagogy, and that each has a time and place in which it is the more effective option, and as such, we will discuss both throughout the chapter.

2.2 Why Do Collaborative and Cooperative Learning Work?

Drawing from different epistemic foundations, a range of theoretical perspectives has emerged to illuminate how collaboration leads to learning (Hmelo-Silver et al., 2013). Among these, the two key theoretical schools here are sociocultural theory and cognitive and sociocognitive theories. Despite both being fundamentally grounded in a constructivist approach to learning, which precedes from the idea of students as active constructors of their understandings rather than mere receptors of
knowledge, each provides different explanations for the phenomena associated with successful learning experiences. Based in the Vygotskian view of learning, sociocultural theory focuses on socially mediated cognition, that is, the idea that learning occurs through socially constructed artifacts, including language. In this context, the effectiveness of collaborative learning comes from the opportunity to learn how to be an engineer by talking about engineering concepts, engaging in the processes of the engineering community, and using the tools, artifacts, and language of the engineering industry (e.g., authentic problem-solving tasks, software used by engineers). Cognitive theories posit that participating in a group initiates the types of cognition that result in learning, such as retrieval, rehearsal, and experiencing cognitive conflict when a peer has a differing idea or opinion (Webb, 2013). Students need to have opportunities to discuss ideas with their peers in order to engage with different perspectives, to rehearse and verbalize their own thinking, and to ask questions.

From a cooperative learning perspective, the success of group learning is grounded in social interdependence theory. First defined by Deutsch (1962), social interdependence theory states that social interdependence exists when goals are shared by individuals and each individual’s outcomes are based on the actions of others. Social interdependence can be both competitive (some win and some lose) or cooperative (all win or all lose). Thus, cooperative learning occurs when groups have a common goal and collective success or failure relies on the actions of all group members.

2.3 The Benefits of Collaborative Learning

Research across the field of engineering education and the learning sciences emphasizes the importance of collaborative learning for a range of educational outcomes, including learning and problem-solving as well as persistence in STEM fields and career preparation (e.g., Barron & Darling-hammond, 2008; Hmelo-Silver & Chinn, 2016). Engineering education research specifically highlights the value of using collaborative tasks for learning and increased student engagement as well as for the development of collaborative skills for future careers (Borrego et al., 2013; Johri et al., 2015).

2.3.1 Increased Persistence in STEM Fields

Equitable participation in STEM fields and the experiences of minoritized students in STEM-related programs and professions have been matters of great concern for several decades (Adelman et al., 1998; Felder, 1994; NRC, 1994; Tao, 2016). Researchers have examined several issues related to engaging K–12 students in STEM courses as well as the nature of the experience of minoritized students in early undergraduate courses. These studies suggest that class sizes, dense theoretical content, and a focus on memorization or drill-and-practice assignments can be alienating both from peers and from the goals of the subject area. Consequently, students often feel that the content they are studying bears no connection to their original reasons for entering the field (Ballen et al., 2017; Pattison et al., 2020).

Collaborative problem-based activities have been identified as mechanisms for addressing many of the difficulties that arise in STEM courses (e.g., Fullilove & Treisman, 1990; Margolis & Fisher, 2002; Pattison et al., 2020). Kalaian et al. (2018) performed a meta-analysis of small-group learning pedagogies in engineering and technology education programs. They report an effect size of .45 in favor of group learning, which, for the complex field of education research, where multiple variables are likely to influence the effect being studied, is a substantial result (Kraft, 2020).

At the same time, as one might expect with such an effect size, results from individual research studies are mixed. Van Dusen and Nissen (2020) report on a study examining the intersectional nature of race/racism and gender/sexism using the LASSO database of 13,857 students in first-semester physics courses. The authors concluded that collaborative learning experiences improved
equity, with all students learning more in collaborative than in lecture-style instruction; however, it did little to foster equality, as all groups improved equally. Another recent study (Mollet et al., 2021) reports that, although participating in peer learning activities was important for sustaining GPAs among minoritized STEM students, collaborative learning in groups where these students were in the minority were not seen to be helpful. This may indicate a need to pay more attention to status issues and address them directly in the creation of collaborative activities. Similarly, Stump et al. (2011) analyzed the results of two surveys of engineering students asked to report on their own collaboration, self-efficacy, knowledge-building behaviors, and course grade. Although these behaviors were significantly predictive of course grade, female students were more likely than male students to report using collaborative learning, and those who used collaborative learning were more likely to get a B than an A or a C. These results all point towards the potential benefits of collaborative learning, while also highlighting the complex nature of pedagogical innovation and recognizing gaps in our understanding of how best to create learning experiences that bring traditionally minoritized students into engineering and STEM more broadly.

2.3.2 Successful Learning Outcomes

Cooperative learning, collaborative learning, and group problem-solving activities are some of the most heavily researched topics in the field of education (Barron & Darling-Hammond, 2008), with most studies finding that these forms of learning yield positive effects. A series of meta-analyses and review articles provides a bird’s-eye view of the literature, showing an overall positive effect of group activities on learning outcomes. For example, Kyndt et al. (2013) report on 65 studies conducted after 1995 that compared real-life classroom-based cooperative activities with traditional, lecture-based learning experiences. They reported an overall effect size on achievement of .54, another unusually high effect size for education research. Nokes-Malach et al. (2015) summarize findings from laboratory studies that show groups outperform individuals on tasks including memory, categorization, and problem-solving. However, they also note that the classroom-level data is more complex; most classroom-based studies agree with the lab studies’ findings, but some show that not all groups have the same experiences. These meta-analyses suggest that collaborative learning experiences have the potential to create more productive learning outcomes but also indicate that success may depend on a large research team implementing the intervention, which may be difficult for individual instructors to replicate in a complex classroom environment. In the sections that follow, we will look closely at aspects of implementing collaborative learning in classrooms that determine whether and how it yields successful learning outcomes.

2.3.3 Collaborative Skills and the Need to Prepare for Careers

Industry professionals have increasingly recognized the importance of collaborative skills in the engineering workplace, where more and more work is done by teams and in groups. Engineers are more than ever required to work collaboratively to tackle global problems, leading to a call for more authentic learning experiences in engineering programs (e.g., Agrawal & Harrington – Hurd, 2016; Liu & Wayno, 2008; Vergara et al., 2009). Researchers have begun to dedicate considerably more effort to both assessing and documenting what counts as collaborative skills (e.g., OECD, 2017) and how to teach them (Borge et al., 2018).

The PISA framework (OECD, 2017) for assessing collaborative problem-solving skills is based on four features of problem-solving that have been identified and analyzed in the literature: exploring and understanding, representing and formulating, planning and executing, and monitoring and reflecting. Researchers have directly connected these four features to three core collaboration skills: establishing and maintaining shared understanding, taking appropriate action to solve the problem,
establishing and maintaining team organization to create a 12-part matrix of collaborative problem-solving skills. Similarly, Hesse et al. (2015) proposed a framework for teaching collaborative problem-solving skills that builds on the ATC21ST™ criteria, which mandates that the skills should be measurable both in large-scale assessments and in classroom settings and that they must be teachable (OECD, 1999). Under this framework, two skill sets are highlighted: social process skills and cognitive process skills. Social process skills are divided into the categories of participation, perspective taking, and social regulation. Cognitive skills are divided into task regulation, learning, and knowledge building. Indicators for subelements of each of these skills are identified, with a description of what these would look like when present at low, medium, and high levels. This list of skills provides an accessible set of behaviors from which to teach students how to collaborate and provide insights to instructors on how to assess collaboration skills.

However, research indicates that merely engaging in collaborations may not sufficiently develop students’ collaboration skills; it is important to provide opportunities for students to explicitly learn collaboration skills, to reflect on their own experiences, and to learn to diagnose and address difficulties within their group dynamics (Barron et al., 2009; Borge et al., 2018; Mercier et al., 2009). In Mercier’s study, 19 stable groups who worked together weekly during the 7th, 8th, 9th, and 10th weeks of the semester showed low-level collaboration in week 7 (the first week working as a group), which remained low across the four weeks (Mercier et al., 2015). While this longitudinal analysis of interactions is rare, it resonates with other research that finds that groups who struggle in their interactions may not be able to repair and/or improve their processes without intervention (e.g., Barron, 2003; Kozlowski & Ilgen, 2006; Mercier et al., 2009).

Over time, researchers have examined different ways to support students during collaboration in order to improve their interactions. For example, Fischer et al. (2013) argue that external scripts can be used to scaffold the development of internal scripts, which allow learners to become better collaborators in future activities. Studies also indicate that students engage in higher-quality interactions when provided with guidance for how to engage in collaboration, whether in the form of scripts (e.g., Kester & Paas, 2005; Weinberger & Fischer, 2001), models (e.g., Rummel et al., 2009), or prompts and activities requiring them to reflect on the interactions (e.g., Cortez et al., 2009). A key feature of the model proposed by Fischer et al. (2013) is the appropriate fading of external scripts as students become more accustomed to collaborative activities and develop internal scripts to guide their actions. As yet, however, few studies have observed students for long enough to track the development of these internal scripts. Borge and White (2016) provide some insight into how students respond over time, reporting on the use of strategies and tools to improve collaboration over an 11-week science unit. Their findings suggest that students can learn to use strategies provided to them, and the quality of their interactions improved over time as they used these strategies more effectively with practice.

In sum, the literature identifies the necessity of teaching students to collaborate but shows that merely placing them in groups, while common, is somewhat ineffective. Techniques can be used to support collaboration, although more research is needed to indicate which are most useful and which are most useful in engineering courses.

2.4 Engineering Education Standards

In the United States, accreditation criteria have explicitly recognized collaboration as a crucial component of an engineering education (ABET, 2018). This was formalized with the change in criterion 3 (student outcomes) from “an ability to function on multidisciplinary teams” to “an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives,” which was implemented during the 2019–2020 cycle (ABET, 2019–2020, 2019).
Similarly, the European Network for Accreditation of Engineering Education specifies that bachelor’s graduates should have the “ability to effectively communicate information, ideas, problems and solutions with engineering community and society at large” and should also be able to “function effectively in a national and international context, as an individual and as a member of a team and to cooperate effectively with engineers and non-engineers” (ENAEE, 2008). The International Engineering Alliance, through its Washington Accord, specifies that graduates should “function effectively as an individual, and as a member or leader in diverse teams and in multi-disciplinary settings” (IEA, 2021). Clearly, international accreditation agencies recognize the role of interdisciplinary teamwork in professional engineering contexts and promote educational contexts in which students learn to effectively frame, address, and solve problems collaboratively. However, despite more than a decade of this heightened focus on teamwork and collaboration, industry experts still see a great deal of room for improvement. For example, a survey conducted by the Association of American Colleges and Universities reported that 63% of the 400 employers surveyed felt graduates were not prepared to work in teams effectively and were ill-prepared to use technologies to solve a problem (Hart Research Associates, 2015). There is still much to be done in effectively designing integrating experiences that will allow students to develop collaborative learning skills as part of their undergraduate training.

2.5 Addressing Diversity, Equity, and Inclusion in Collaborative Learning

Despite the many benefits of collaborative learning in engineering courses, research has illuminated negative aspects of teamwork related to gender (e.g., Beigpourian & Ohland, 2019; Laaser et al., 2003; Tonso, 1996), race/ethnicity (e.g., Blosser, 2020; Chen et al., 2015; Cross & Paretti, 2020), and sexual orientation (Cech & Rothwell, 2019; Cech & Waidzunas, 2021), where students can be further marginalized in engineering teamwork (Meadows et al., 2015). Indeed, marginalized students are apt to “experience group environments differently not because they lack sufficient skills or resources, but because cultural and social norms create barriers not typically experienced by students from dominant groups” (Meadows et al., 2015, p. 12). Often-times, minoritized students are burdened with “stereotype management” (McGee & Martin, 2011) which might contribute to their discomfort in course situations (Meadows et al., 2015), with a negative impact of their sense of belonging. Moreover, because many (quantitative) studies aggregate minoritized students into one group, failing to account for the intersectionality of multiple groups, we still have much to learn regarding the best ways to create an inclusive environment in collaborative learning. While this chapter will explicitly discuss DEI considerations in Section 3.1.2, “Group Composition,” we recognize the need for additional research in collaborative learning.

2.6 Issues in Using Collaborative Learning

Despite decades of research indicating the value of collaboration in learning contexts and clear evidence that collaborative learning enhances classroom experiences, the actual implementation of collaborative learning has several drawbacks (Nokes-Malach et al., 2015). Teaching both short-problem–based collaborative activities and longer–term projects can present a number of challenges for instructors, many of which are understudied (e.g., Mercier et al., 2009; Takai & Esterman, 2019). These challenges are often associated with inequities in participation and poor social interaction skills but can be addressed through task design, classroom interventions, and spending time to develop social skills and group norms during the course. These issues can make teachers and instructors reluctant to use collaborative and cooperative learning pedagogies (Gillies & Boyle, 2010;
Shehab & Mercier, 2019). In Section 3.4, we discuss the role of the teacher in implementing collaborative learning in more detail, although note that it is an area that needs significant future research.

One of the most frequent complaints from students who are assigned collaborative learning projects is that one or more of their group mates did not complete their share of the work and/or did not participate in group activities (Tenenberg, 2019). Known as free riders, these students appear to sit back and allow others to complete the work. The free rider is left with a less-successful educational experience, and the rest of the team has to work harder to make up for the free rider’s indifference, often becoming frustrated with and resentful of the task. While this can be particularly problematic in a multi-week project, it can also be harmful in shorter collaborative activities.

Another problem that arises in collaborative projects, sometimes in relation to a free rider issue, is the domination of the group by one or more students (Salomon & Globerson, 1989). In this situation, a single student or subgroup of students takes over and either does not engage in collaborative knowledge-building discussions yet makes decisions and assigns work to the other group members or completes all the work alone. This can negatively impact the educational experience of less-involved students, may result in all students missing the opportunity to learn more about collaborating, and may yield a poorly designed final product or less elaboration of ideas within a group if one or more member is rushing to complete the project.

Another related issue is that of social loafing, wherein some or all the students in a group reduce the amount of effort that they would typically put into a class assignment. Borrego et al. (2013), who deliver a systematic review of the literature on student teams in computer science and engineering, note that social loafing was the most frequently cited negative team behavior. Social loafing is often viewed as an issue of motivation. It can be addressed through assessment practices, although some argue that increasing the inherent value of the task for students is a more effective way of treating the problem (Karau & Williams, 1993, 1995).

Groupthink, in which agreement and cohesion between group members become more important than fully exploring a topic, is another well-documented issue in the research on teamwork in education (e.g., Bénabou, 2013; Janis, 1991). There is a significant body of literature on this topic, which is particularly prevalent within the organizational psychology literature. In previous studies, we have documented a series of issues that may arise in student teams when groupthink dominates the early stages of a design project (e.g., Mercier et al., 2009) and suggest that, in designing the phases of a project, strategies such as presenting multiple ideas be included.

These negative effects are associated with a variety of causes: tasks that are not truly group-worthy (see Section 3.2), students who do not understand the purpose of participation, students who do not know how to participate or to recruit other members’ participation, or students who are struggling with the content. Different goals for the activity can also lead to these issues, as when students who are strongly focused on getting a high grade are required to work with students who are less invested in the course.

Research grounded in status theory points to the importance of attending to an individual’s status within the group and how perceived status can impact the way group members interact (e.g., Cohen & Lotan, 1997). When a group collectively identifies one member as low status with respect to the task, they tend to exclude that member or disregard their ideas (Berger et al., 1980). This can be particularly relevant for interdisciplinary teams, where preconceptions about the value of the different disciplines may impact the way contributions are valued, work is assigned, and/or group assessments are conducted (Booker et al., 2009). Scholarship on Complex Instruction (e.g., Azizan et al., 2018; Cohen, 1994) indicates that it is possible to configure classroom instruction and tasks so as to identify the value group members bring to a project and thereby promote more equitable participation.
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3 The Four Ts of Collaborative Learning in Classrooms

In our prior work, we identified four core aspects of collaborative learning in classrooms and recommended that more attention be paid to each of the four aspects so that this pedagogy could be implemented more successfully (Mercier & Higgins, 2015). As before, these four aspects are teams, tasks, tools, and teachers. Although the amount of research dedicated to each aspect has varied, all four overlap with one another to some degree. In the sections that follow, we take each of these four aspects and review relevant studies and the overall research stream. We have also included assessment as a subsection of teaching, since, although it is part of the teacher's role (e.g., Kaendler et al., 2015), drawing it out as a specific section allows us to highlight the importance of assessment to the collaborative learning experience.

Learning also takes place in a specific context, and attention to that context, both in terms of the norms that are established by the teacher and class as well as to the classroom design, available tools, etc., is essential to thinking about how to implement collaborative learning activities.

As noted earlier, we reviewed publications in four engineering education journals in order to generate an understanding of where the field is positioned in relation to these four core areas of collaborative learning. The distribution of papers is shown in Table 19.1. Of the 285 papers we collected from these journals since 2010 (since 2019 for SEE, the first year it was published), the majority were primarily related directly to teams (150), followed by tasks, assessment, teachers, and tools. Around 161 papers received one code, 85 two codes, and 11 received three codes. One paper (Marbouti et al., 2019) was classified as discussing teams, teachers, tasks, and assessment; 27 articles, all from Studies in Engineering Education, did not receive any classification. The majority of these were review papers, position papers, or papers discussing methodological issues in the field.

3.1 Teams

On a basic level, the literature agrees on certain prerequisites for functional collaborative teams. While they have been written about using a variety of terminology, there is a broad consensus that team members need to communicate effectively with each other, be responsive to other team members, and be willing to cooperate and compromise to accomplish tasks (Hmelo – Silver et al., 2013). Commitment to supporting teammates has also been identified as an essential element in successful groups (e.g., Bratman, 1992), which is particularly relevant in collaborative learning contexts, as making sure that all team members understand the assignment is essential if all students are to have equitable learning experiences.

Beyond these fundamental requirements, a significant cross-section of research in collaborative learning has focused on the functions of teams and the types of interactions that are most often associated with successful outcomes; it is generally accepted that the quality of students’

Table 19.1 Topics Covered by Papers about Collaboration in Engineering Education Journals

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<th>Journal</th>
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<td>Teams</td>
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<td>Journal of Engineering Education</td>
<td>22</td>
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<tr>
<td>International Journal of Engineering Education</td>
<td>79</td>
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<tr>
<td>European Journal of Engineering Education</td>
<td>46</td>
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<td>Studies in Engineering Education</td>
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interactions is pivotal to successful learning experiences (Barron & Darling- Hammond, 2008; Hesse et al., 2015). High-quality interactions include co-creating a joint understanding of the problem space (Roschelle, 1992), creating joint visual representations (Mercier & Higgins, 2015), building on each other’s ideas (Barron, 2003), and responding to questions with elaborated explanations (Webb, 2013).

Successful teams attend to two dimensions of collaborative interaction: the social or interactional space and the problem or cognitive space (Barron, 2003). The social or interactional space includes participation, perspective taking, and social regulation, while the cognitive space includes task regulation and learning, as well as knowledge building (Hesse et al., 2015). In the interactional space, it is important that students engage with peers, persist with the task, participate in perspective taking, that is, responding to teammates, listening, and adapting based on their perspectives, and maintaining social regulation. Social regulation is described in multiple ways across the literature and encompasses self-directed behaviors, such as negotiation, self-regulation, monitoring one’s own understanding in relation to the group, as well as socially shared regulation of the group. Socially shared regulation refers to the meta-cognitive, deliberate processes required for groups to regulate their participation and behavior (Hadwin et al., 2019).

Research in engineering education also emphasizes the importance of teams; indeed, most of the papers we reviewed focused on this topic. Many of these papers highlight elements of team composition (e.g., Griffin et al., 2004; Mikic & Rudnitsky, 2016), the development of teamwork skills (e.g., El-Sakran et al., 2013; Hadley, 2014; Maturana et al., 2014), and the impact of diversity of group members or ideas (Fiia & Purzer, 2014; Lau et al., 2012; Vanhanen & Lehtinen, 2014). We also found a large subset of papers examining interdisciplinary teams, many of which indicate that this is a substantially more complex form of collaboration that requires explicit attention (Goldberg & Malassigné, 2017; Gulbulak et al., 2020; Hoople et al., 2019; McNair et al., 2011; Shooter & Mcneill, 2002).

While significant work has gone into identifying the behaviors associated with successful groups, we also need to understand how to foster these behaviors (Mercier, 2017). Classroom evidence, alongside general experience, shows that many group activities are not productive, and that collaborative learning is rarely successful without significant support (e.g., Nokes – Malach et al., 2015). Preparing students to work effectively in groups is essential, not only for their experience in the course, but also for the development of collaborative skills that they will take into future courses and the workforce (Barron et al., 2009; Smith et al., 2005). Thus, in the next section, we present the different mechanisms for fostering behaviors that are typically demonstrated in successful groups.

### 3.1.1 Scripting Collaboration

The literature offers several mechanisms for fostering productive team behaviors: scaffolding and scripting for promoting social interactions, cognition, and metacognition (Ertmer & Glazewski, 2019; Reiser, 2018; van de Pol et al., 2010); engendering interdependence (Johnson & Johnson, 1984; Smith et al., 2005); and the ICAP framework: interactive, constructive, active, and passive (Chi & Wylie, 2014), which refers to the degree of student-centeredness. Each of these mechanisms will be briefly described in the subsequent part of this section.

Rooted in Vygotsky’s zone of proximal development (Vygotsky, 1978), scaffolding describes temporary support designed by the instructors to improve the effectiveness and efficiency of learning and interaction. While scaffolds are elementally defined by contingency, fading, and transfer of responsibility (Wood et al., 1976), research also indicates that supportive elements like technology, tools, artifacts, resources, and even environments may be considered scaffolds when they aid student learning and interaction (Nadir, 2021; Puntambekar & Hubscher, 2005). Scaffolding can be provided at different levels: cognitive, linguistic, affective, social, metacognitive, and strategic planning.
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(Baxter & Williams, 2010; Belland, 2017; Belland et al., 2013), all of which are necessary during collaboration.

In engineering education, scaffolding (Wood et al., 1976) is especially important because it requires that students collaboratively solve complex and ill-structured problems, often in a project-based learning setting (Moallem et al., 2019; Tucker et al., 2020; Frank et al., 2018). Frank et al. (2018) demonstrated the effect of scaffolding on complex problem-solving and provide scaffolds for collaborative projects to be implemented during different phases, like problem definition, information evaluation, mathematical model development, and communication and argumentation. Consistent with this, Ge and Land (2004) promote the use of question prompts as scaffolding techniques to facilitate peer interactions during the four processes of ill-structured problem-solving: representation of the problem, development of solutions, justification of solutions, and monitoring and evaluation. The prompts are designed to direct teams’ attention to the crucial points of the problem and solution space while encouraging different perspectives from the team members.

Scripting collaboration is another way to support students working in groups. Scripts can be either epistemic or social (Weinberger et al., 2005), guiding students to engage in the task and collaborate with their teammates. Epistemic scripts are often embedded in the task itself and can be seen as scaffolds. They may come in the form of a table or other representation that students fill out as they work through the task, which can guide the team to approach the task in a specific sequence or ensure that particular elements are not missed. Epistemic scripts may also guide students through the processes necessary for a particular task (e.g., look for evidence, look for ideas that contradict your claims, etc. or, in the case of introductory engineering courses, create a free-body diagram before you attempt to generate and solve an equation).

Social scripts aim to prompt the type of interactions that are most likely to foster knowledge building and help structure the way students work together. A classic example of a social script assigns a single paper to a pair of students. One student takes on the role of explainer, and the other of listener. The listener must try to understand what the explainer is telling them and add any missed details after the explainer finishes their part of the task (e.g., O’Donnell, 1999). More common classroom examples include “think-pair-share,” where students are given time to think about a problem, then share or discuss with a peer, and finally share out to the class. This type of script can be adapted for other contexts and can be used effectively in problem-solving tasks in which students are instructed to read the problem alone, discuss it with their peers, generate solution options alone, share them with peers and determine a plan together, work on calculations alone, and then compare and complete the task. While this may feel unnecessary in higher education, often students need help understanding the different stages of a task or thinking about what they want to discuss with the group. This type of script also prevents students from simply charging ahead and trying to solve the problem without fully discussing it with their peers or grasping it themselves.

Scaffolding or scripting for social interactions creates interdependencies (Buchs et al., 2017; Marra et al., 2016), which in turn create pathways for productive dialogues between team members. The theory of social interdependence helps us understand the different types of interdependencies that instructors can draw on in designing collaborative tasks. Positive interdependence influences the degree of interaction between team members, which in turn impacts team effectiveness (Johnson & Johnson, 1984). A systematic review (Borrego et al., 2013) concluded that interdependence is one of five key elements of successful teamwork in engineering education. Interdependence mediates interactions between team members, fostering reciprocal relationships between them by creating a concrete agenda for collaboration. This agenda comes from different interdependencies categorized based on their focus: means or ends. When focused on means, goal and reward interdependencies are applicable. When focused on ends, resources and role interdependencies are applicable (Johnson & Johnson, 2008a). Yet all types of interdependencies are not theoretically equivalent (Ortiz et al., 1996), as particular combinations of interdependencies are more effective than others (Johnson &
Common ways of structuring interdependence include dividing tasks, sharing limited resources, and assigning specific roles to individuals based on disciplinary and course-related objectives (Johnson & Johnson, 2008b). Pinho-Lopes and Macedo (2016) compare course implementation using collaborative and cooperative learning approaches for project-based learning in a geotechnics course in a civil engineering program. In the version of the course that follows cooperative learning pedagogy, role and task interdependence and individual and group accountability are applied through a set of instructional decisions based on the jigsaw system. Cámara-Zapata and Morales (2020) describe how the roles of presenter, evaluator, and observer were assigned and rotated between the team members in an introductory physics course on mechanics and thermodynamics. In line with these, Baligar et al. (in press) detail how the interdependencies of task, reward, goals, and resources can be applied to design instruction for engineering design problems at first-year undergraduate engineering education. The interventions and task aids designed for the four phases – information gathering, problem definition, concept generation, and detailed design – elicited better performance without aggravating interpersonal processes and individual well-being and learning. This is specifically important as increased interdependence often leads to conflicts and arguments (Opdecam & Everaert, 2018). In another recent study, Beddoes (2020) introduces a conceptual framework called interdisciplinary teamwork artifacts and practices (ITAPs), which proposes a set of artifacts and practices designed to engender interdependence, avoid conflict, and promote trust and shared teamwork and taskwork mental models for interdisciplinary teamwork in engineering education. The artifacts are aligned to orient, operate, level, propose, align, and structure taskwork knowledge, including task procedures and strategies and functions and forms, as well as teamwork knowledge, including roles, responsibilities, and team interactions.

Lastly, another practical framework that can influence the design and study of interactions in a collaborative learning environment is ICAP (interactive, constructive, active, and passive), which puts students’ engagement with content and peers along a continuum from passive to interactive (Chi & Wylie, 2014). At the level of “interaction,” this framework focuses on productive dialogues between peers who respond to each other constructively. It identifies the indicators of “interaction” as those that build on the views and perspectives of peers, seek elaboration, identify inconsistencies, generate arguments on the correctness of a view, and elicit justification for a view. This framework can also be used as a yardstick to assess the effectiveness of the scaffold/script in eliciting productive dialogues between peers in a collaborative learning setting.

In this way, instructional design using scaffolding/scripting has the potential to reduce dysfunctional team processes (Mathieu & Rapp, 2009) that lead to coordination and task allocation delays, specifically for students new to team-based problem-solving experiences like problem-based learning and project-based learning. Overall, positive interdependence, coupled with individual accountability, is known to mitigate social loafing and free riding, which, as discussed earlier, often negatively impacts team morale (Johnson & Johnson, 1984).

### 3.1.2 Group Composition

Significant attention has been given to group composition, with a focus on understanding how the different elements an individual brings to a collaborative group influence the group’s experience. Individual features may range from personality traits (Boudreau & Anis, 2020), gender (Dasgupta & Stout, 2014), prior relationships or friendships (Maldonado et al., 2009), GPA, or prior performance in the course or related courses. There is some evidence that the gender composition of a team can be impactful; Dasgupta and Stout (2014) identify female-majority and sex-parity groups as initially important for female students despite having little or no effect on the anxiety of senior female
students in the longer term. Meadows and Sekaquaptewa (2011) report on participation in presenta-
tions among mixed-gender groups, noting that male students talked more, and about more technical
content than female students. In addition, male students rated their own leadership and performance
higher if there were fewer males in their group.

Research also suggests that minority status in the classroom, which often correlates with nega-
tive peer and instructor perceptions of ability stemming from racist and sexist stereotypes, can have
a negative impact on minoritized students’ participation in teams, which detracts both from their
learning experiences and the overall quality of group discourse. The influence is bidirectional, with
students who fall into these categories being less willing to participate and students who fall into
majority categories being less willing to listen to or build upon the ideas of minoritized students
(see Esmonde, 2009 for a review). One common strategy is to ensure minoritized students are not
isolated on teams (e.g., a female student in a majority male course is not in a team with only male
students). In addition, both course-level interventions and addressing issues related to perceptions of
peers’ status directly have the potential to counteract these issues but require the instructor to exam-
ine their own biases and explicitly address them (e.g., Wagner, 2014; Webb et al., 2019). With this
in mind, it is also important to note evidence suggesting that the experience of working on a diverse
team improves attitudes towards minoritized students and those who do not speak English as fluently
as native speakers (e.g., Cabrera et al., 1998; Godwin et al., 2017). Thus, working to mitigate the
effects of minority status appears to be positive for all students, and likely to have long-term impacts
on their future collaborations.

However, evidence on the specific impacts of individual-level variables is mixed, with contradic-
tory results across studies. Drawing on the literature on team effectiveness, Borrego et al. (2013)
note that the approach of trying to isolate the effect of a single variable on the fluid and emergent
nature of collaborative groups is problematic. It is unlikely that a single variable will be predictive
of behavior across situations, and behaviors will vary during a multi-week project as students deal
with emergent issues. Instead, they argue for more attention on the alignment of processes and goals,
which suggests that, for team formation, efforts to ensure teams are aligned in their goals for the
course or project, as well as in their preferred processes (which may include simple things such as
availability for meetings at times of the day and preferences for project topics), are paramount. Their
study also highlights the importance of providing students with guidance in the development of their
processes and in creating opportunities to restore broken group processes as necessary.

However, regardless of the general inconclusiveness of research on group formation, stu-
dents need to be grouped somehow, and particularly in interdisciplinary or online courses that
draw students from multiple time zones, there may be requirements for group composition that
include ability to meet at certain times. In a review presented by Parker et al. (2019), the divi-
sion of students into capstone teams was guided by six different approaches. The first of these
approaches is the simple random assignment of students to teams, which is seen as the least
time-consuming and a strategy to prevent groups being formed based on friendship or prior
experiences together. However, Parker et al. (2019) report that it is the least frequently used
and is associated with bad team experiences, with little to justify group membership, which can
be particularly problematic over a long-term project. Two forms of student-formed teams were
identified: no guidance and conditional self-formed teams. The first allows students to select
their own teammates, and some may come to capstone course with complete or partially formed
teams. Fully formed teams can join the course with a lot of motivation to work together on
their chosen project, while partially formed teams who have members added may struggle with
ownership and domination of those in the original group. It is also likely that some groups may
be formed out of those who didn’t come to the course with a group, which may be problematic
for reasons that include poor prior performance by these students (and so they were not invited
to join groups) or lack of motivation to participate in the course. Conditional self-formed teams
are provided with a list of criteria by the instructor for team membership, and team members are selected to meet these criteria. This can result in teams with the necessary balance of skills or prerequisite knowledge for the project, while eliminating issues associated with friendship-based groupings. They are also likely to give students an experience more similar to those they will experience once employed, where group membership is often driven by project needs, not member preferences. Instructor-led team formation options fall into three categories: student skills, student preferences, and client preferences. For student skills, the instructor conducts an audit of skills (e.g., a mini-project, collection of résumés, asking students to apply for certain roles, etc.). While there is benefit in having students identify their own skills, this is a labor-intensive activity for instructors and may lead to teams where students work to their existing strengths rather than learn a new skill set. Instructor grouping by student preferences may focus on the project or topic preferences of students, whereby the instructor groups students based on a set of choices or rankings made by students. They may also use areas where students identify a need for development and place them in roles to develop those skills. Additionally, student preferences may be used to exclude certain groupings, where students identify people they do not want to be in a group with. Finally, instructor-led team formation can be based on client preferences, where project sponsors may meet with members of a class beforehand and then select those they wish to work with, potentially privileging students who perform well in interview situations. All instructor-led approaches have the potential to be time-consuming and may result in preferences not being met (due to an imbalance of preference for project types, team members, etc.)

Computer-supported team assignment tools can be used to account for a number of factors simultaneously and group students based on a more quantitative rubric which may be identified prior to the course by instructors (e.g., CATME, Layton et al., 2010). Of concern is students’ willingness or eagerness to accept instructor-assigned teams, leading to a weaker sense of ownership. These concerns can be alleviated by engaging teams in specific team-building activities in the initial stages of projects (e.g., Hastings et al., 2018; Mercier et al., 2009). More recent work also points to the potential of having students participate in selection of the assignment criteria but allowing the tools’ algorithm to create teams, leaving students more aware, and more content with, the group formation process (Hastings et al., 2022).

3.2 Tasks

Tasks are an integral component of collaborative learning. The tasks should scaffold and direct the groups’ focus towards the prescribed learning objectives. Problem-based learning approaches provide an effective way of bringing real-world scenarios into the classroom by presenting the problem first and then finding the solution (Barrows & Tamblyn, 1980; Kolmos & Graaf, 2014). In engineering classrooms, collaborative tasks are often implemented using problem-based learning activities (Di Pietro et al., 2019; Perez – Poch et al., 2019; Zhang et al., 2018). Problem-based learning reduces students’ cognitive load by allowing them to draw on their expertise via verbal interactions (Hmelo – Silver et al., 2013). These tasks differ based on the context in which they are being implemented (Boxtel et al., 2000).

There are two types of tasks instructors use to support learning, well-structured and ill-structured tasks (Jonassen, 2004). Well-structured tasks facilitate the students’ interactions (Roth & Roychoudhry, 1992). They have convergent solutions and set well-defined parameters for solving the task. Students can be directed to exchange information through different task features like reflection (Turns et al., 2014). Assigning tasks that use methods like the “jigsaw” or that “script” the process provides students with a set of rules or instructions on how to interact with their peers and collaborate (Kagan, 1989; Dillenbourg, 2002). These tasks are often paired with cooperative
learning, where students have set roles and their interactions are structured. However, care must be taken to avoid overstructuring the group interaction process, which could be detrimental to the intrinsic motivation of the students, thereby disturbing natural interaction processes (Dillenbourg, 2002).

The second category is ill-structured tasks. These tasks pose situations lacking necessary information and having multiple solutions and solution paths. Ill-structured tasks are more suited to collaborative learning (Cohen, 1994). The problem-based learning approach lends itself well to ill-structured tasks as it requires posing the problem first. Ill-structured tasks require more than the domain knowledge and justification skills required for solving problems (Shin et al., 2003). They require additional skills relating to regulation of cognition, which involves planning, monitoring, and re-evaluating goals (Chin & Chia, 2006). Studies have shown that leveraging tools to aid in the development of these skills has helped students effectively collaborate (Fidalgo – Blanco et al., 2018; Pazos et al., 2019).

Engineering tasks specifically designed for collaborative work that take full advantage of our understanding of how to support learning and interactions are much needed (Shehab & Mercier, 2017). In creating collaborative tasks, it is important to consider the difficulty of the task presented to the students so that it is neither too easy, leading to a single student completing it, nor too difficult for the group. The intermittent development zone (IDZ), a corollary to Vygotsky’s zone of proximal development (ZPD), describes the space between what a learner can and cannot learn without the assistance of peers (Vygotsky, 1978; Fernández et al., 2015). Tasks should scaffold peers to interact with each other within the IDZ so as to facilitate collaboration. Tasks should also provide multiple layers of meaning, allowing students to gain multiple perspectives and to think about the problem and communicate their ideas (DeLiema et al., 2015). In addition, reflecting on elements of scripting interactions described in Section 3.1.1, there is a clear need to consider how best to support interaction through the task features.

An additional element of collaborative tasks is reflection, which involves students revisiting features of their experiences and attaching meaning to them that can guide future actions (Turns et al., 2014). Studies have shown that reflection is a necessary part of effective collaborative activities and design projects (Burkholder & Wieman, 2021). Students tend to improve their reflection specificity over time, and their reflections are a good predictor of academic performance (Anwar & Menekse, 2020). Interdisciplinary tasks and projects involving interdisciplinary teams allow students to gain different perspectives (Hoople et al., 2019). Continuous self- and peer assessment can be incorporated into tasks as a way to improve student behavior and the reliability of feedback from peers (Foong & Liew, 2020). Studies in engineering education journals have explored the role of peer assessment (Alba-Flores & Rios, 2019; Carberry et al., 2016) and the impact of peer assessment on teams (Foong & Liew, 2020; Mandala et al., 2018). Findings indicate that peer review increased students’ awareness of collaborative behaviors, that the evaluations indicated improved quality of collaboration over time, and that both providing verbal feedback and spending more time providing feedback positively impacted students’ learning experiences.

Although reflective processes and their benefits have been the subject of considerable research, other task features and how they foster student interaction and encourage collaboration and learning are less understood. More micro-level understanding of tasks and their influence on student interaction can help us understand how to leverage these tasks to facilitate collaboration in a more meaningful way among students.

In the engineering education journals we reviewed, many papers focused on both the tasks and teams dimensions. A small but important subset of studies explored how task elements impact the manner in which teams interact, in particular focusing on the role of agency in decision-making or task framing (Burkholder & Wieman, 2021; Svihla et al., 2021). Several papers report on issues that emerged in groups, some of which were attributed to limitations in the implementation of
collaboration pedagogy. Successful groups were attributed to the design of implementations that focus on team spirit, assignment, and the rotation of roles within groups, as well as support for effective time management and interdependence strategies (e.g., Berge & Weilenmann, 2014; Missingham & Matthews, 2014; Pinho-Lopes et al., 2011).

### 3.3 Tools

The tools provided to students that support their collaborative learning are essential to the success of this pedagogical approach, although this was the least-discussed category in the engineering education journals. Johri et al. (2013) divide tools into two types: representational tools and relational tools. Representational tools are designed to support the creation of (joint) representations during collaborative activities, while relational tools support interaction between group members. This distinction allows us to consider how both needs will be met when we assign students to groups and either provide or guide students toward, tools that will allow them to represent their solution progress and communicate with each other.

The need for tools obviously differs by context and activity type. Classroom-based collaborations to be completed in a single session rarely need additional support for communication but can benefit from tools to support representations. While research points towards the value of high-tech tools (e.g., Berthoud & Gliddon, 2018; Mayer et al., 2013; Mellingsæter & Bungum, 2015), it is important to note that tools do not have to be technologically advanced to be helpful. Certain low-cost tools can have a profound impact on groups, such as A3 (12 × 17”) sized whiteboards that can be provided to groups as a surface on which to visualize joint representations of problem-solving activities, rather than having each student write in their own personal device or notebook (Essick et al., 2016). In contrast, a semester-long project where students must meet outside of class time may require a suite of tools to help students communicate and manage their interactions, as well as tools to represent their solution processes (e.g., Colomo-Palacios et al., 2020; Kirschman & Greenstein, 2002; Oladirana et al., 2011).

Tools may also be categorized based on whether they were created explicitly for a particular course or topic (e.g., Caballé et al., 2014; Serrano-Cámara et al., 2016) or were already available to the general public but adaptable for use by student teams (e.g., Pazos et al., 2019). The literature points towards value in both approaches, with tools that are designed specifically for a context providing rich learning opportunities for students, but often requiring additional effort to implement or learn to use. Tools that are available more generally often have the benefit of being familiar but may not meet all the requirements of a team and may require trade-offs between instructor control and monitoring (such as communication through a learning management system) or familiarity and distraction (such as using a social media site to communicate) (Tlhaoele et al., 2016).

Recent literature examines new ways of using technology to augment collaborative learning in engineering. Examples of emerging technology that may be suitable for this purpose include tools that are designed to support teachers or instructors during collaboration activities (e.g., Lawrence & Mercier, 2019); collaborative simulation-based platforms to learn engineering concepts, such as online electronics breadboards (Andrews et al., 2017; Horwitz et al., 2017); augmented reality (AR) approaches to software concepts (Schiffer et al., 2019); and AR-supported circuits and electronics (Villanueva et al., 2020). In addition, tools that support teaching large courses more generally, such as those designed to automatically create teams based on particular criteria (e.g., years of CAD experience, familiarity with a programming language, etc.) can make collaborative pedagogies easier to implement.

Imbricating tools within the rest of the framework is also essential. It is useful to consider whether students are prepared to use the tools they are given by the instructor to support their interactions and co-construction of knowledge, whether they are aware of the tools they can use, and whether the team members agree on how tools will be used over the course of a long-term project. It is also
necessary to consider how tools can function to make tasks more accessible, and how teachers can use tools to support their teaching or gain insights into the processes of student groups, as well as to help with in-class intervention or grading.

### 3.4 Teachers

Teachers are a crucial element of collaborative learning, particularly in undergraduate engineering settings, as they are responsible for designing collaborative activities and overseeing their success (Lawrence & Mercier, 2019). However, relatively little research has been done on the role of teachers in collaborative learning (Webb, 2009; Kaendler et al., 2015). In practice, many educators who believe that they are employing collaborative learning strategies are actually missing crucial elements that would enable students to work together more effectively (Johnson et al., 1991). Meijer et al. (2020) have synthesized two principles for designing collaborative learning exercises from the larger collaborative learning literature: individual accountability with positive interdependence (based on Slavin, 1980; Johnson, 1981; Strijbos, 2011) and adherence to eight collaborative components: (1) interaction, (2) learning objectives and outcomes, (3) assessment, (4) task characteristics, (5) structuring, (6) guidance, (7) group constellation, and (8) facilities (de Hei et al., 2016). Arguably, teachers have the greatest influence over all these factors; the previous sections on teams, tasks, and tools all suggest the important role teachers play in developing, structuring, and executing these areas. In planning a class, teachers have a certain amount of latitude over how to reach course learning objectives and outcomes. In addition, they are often the ones in charge of designing course assessments. Teachers are responsible for aligning learning outcomes and assessment in ways that are facilitated with collaborative learning activities, a crucial component in successful collaborative learning. Additionally, instructors make decisions regarding group composition, roles within the group, and sometimes the arrangement of the room (Johnson et al., 1991). Thus, the effort and time the instructor invests in designing instruction for collaborative tasks will be influenced by the students’ previous experience of engaging in collaborative tasks. Based on the students’ proficiency in process aspects of collaborative work execution, it would make sense to design tasks with micro-level interdependency (resources, tasks, and roles) or macro-level (goals and rewards).

Outside of task development, tool selection, and team formation, teachers have a particularly instrumental role in supporting students’ processes during collaborative learning. This support can involve monitoring students’ interactions (e.g., Hmelo-Silver, 2004), guiding student activities, and providing feedback on their immediate or longer-term collaborative efforts (e.g., Mercier et al., 2009; Shehab & Mercier, 2019).

Across the field of engineering education, research on the role of teachers and instructors has also been limited, with less attention paid to this essential element as compared to other aspects of collaboration. Of particular relevance is the work of Gómez Puente et al. (2015), who report on professional development among instructors planning to implement design-based learning. During professional development sessions, the instructors redesigned their own teaching material and then implemented these new strategies in the second year of the study. Results indicated improvement in projects across a number of areas, suggesting that even a relatively minimal (seven-hour) intervention may allow teachers to more effectively implement these types of learning experiences.

#### 3.4.1 Assessment of Collaborative Learning

An essential role teachers play in collaborative learning is deciding when and how to assess it. Assessment in engineering education is a complex topic (Pellegrino et al., 2001), which operates with the goal of educating and improving student performance rather than simply auditing student efforts (Wiggins, 1998). Educational assessment can be used to assist learning, determine individual
achievement, and evaluate programs (Pellegrino et al., 2014) not only in general educational but also in collaborative learning environments. However, assessment has not been a key focus in collaborative learning research over the last two decades. Of 14 meta-studies on collaborative learning design, assessment was mentioned in two (de Hei et al., 2016).

We posit that many of the assessment issues raised by Pellegrino et al. (2014) are also issues in collaborative learning. In particular, we find that the four main considerations or tensions in assessment of collaborative learning are (1) formative vs. summative feedback, (2) individual vs. group (or a combination of both), (3) grading based on effectiveness of the group vs. overall “correctness,” and (4) assessment of product vs. process. Irons and Elkington (2021), in their comprehensive detailing of the theoretical foundations and principles of formative feedback and assessment, provide practical suggestions on how feedback can be structured to maximize its reach and comprehension to students while suggesting that instructors should focus not only on the outputs of groupwork but also on the process. Concentrating on the social aspects of groupwork, Thistlethwaite et al. (2016), in the context of interprofessional education, devised an individual teamwork observation and feedback tool which assesses students’ individual contribution to teamwork at two levels: basic version, which includes 11 observable behaviors, and an advanced version, which lists 10 observable behaviors. These versions are based on students’ maturity in teamwork experiences. Thus, it becomes imperative that the instructors are aware of the quality indicators of effective and efficient collaboration.

Assessment of group processes often comes in the form of peer assessment, where peers are given the opportunity to evaluate their team members’ contributions, generating scores which are sometimes used to provide an individual grade to each student. From a cooperative learning perspective, this can fulfill the goal of individual accountability, although it has the potential to be used as a punishment for team members who did not participate actively. Rather than solely relying on the summative evaluation of peers, opportunities for commentary on group processes during the course (e.g., Mercier et al., 2009) may be more effective for identifying and intervening when issues arise, thus supporting ongoing learning of collaborative skills.

An alternative approach, developed and described by Borge and colleagues (e.g., Borge & Goggins, 2014; Borge et al., 2018, 2020), engages students in assessments of their discussion board posts using a framework of effective collaborative communication behaviors. Teams self-assess their contributions to the group and have the opportunity to discuss how to improve their communication and collaboration, setting goals for how they would like to collaborate in their next activity. Thus, students are involved in self- and peer assessment, albeit in service of supporting their own development rather than assigning grades. While this system is currently limited to text-based communication, emerging use of AI and data analytics to assess collaboration may provide access to students’ processes more readily in the future (e.g., Bachour et al., 2009; Paquette et al., 2018).

4 Conclusion

In this chapter, we have reviewed the literature on collaborative learning, highlighting four important areas that must be attended in implementing collaborative learning in classrooms (tasks, tools, teams, and teachers). Lab-based research shows that collaborative learning activities can be highly effective, and there is no doubt that engineering students need to develop the skills necessary to engage in collaborative problem-solving before joining the workforce. Under the right circumstances, they can do this through well-structured classroom experiences. Our review of the literature, however, reveals several challenges, including the complexities of studying and implementing collaborative learning successfully in classrooms, the reliance on student attitudes towards their collaborative experiences as metrics of success, and the lack of research into the development of collaborative skills over time and into the facilitation of student reflections and metacognition around their most effective group processes.
Studying and implementing collaborative learning are complex endeavors that take place in a complex environment where tasks, tools, and teachers all impact how students function in teams and achieve the goals of the task. In addition, while research has provided us with a good description of what groups look like when they are successful, we are still working to understand how best to get students to engage in the types of interactions that lead to successful outcomes. Research on the design of tasks that successfully support collaboration is still in its infancy (e.g., Tucker et al., 2020), while work on the role of teachers in effectively intervening is also relatively limited and has yet to fully become integrated into the literature of engineering education (Shehab & Mercier, 2019). While emerging literature (e.g., Gómez Puente et al., 2015) indicates that there is potential in short-term interventions for faculty to improve the quality of their teaching materials and courses when using collaborative learning, future research in this area of the field is essential (both in engineering and in education more generally).

A further challenge for the field is the extent to which studies rely on students' self-reported data, despite evidence that students are not necessarily the best judges of what counts as a successful learning experience. Students often prefer lectures, which may result in less learning, overactive learning activities, and projects which require more effort on their part but result in better learning outcomes (Deslauriers et al., 2019). For example, Mostafapour and Hurst (2020) report that students preferred taking a divide-and-conquer approach to their group tasks, which is often more efficient but is unlikely to provide the opportunities to engage in discussion of the material or to co-construct a solution, leaving them without the key skills these tasks were designed to develop. Research that relies on students' preferences may thus lead us in the wrong direction in terms of understanding what is best for learning outcomes. It is also important, given the discrepancy between students' attitudes towards learning experiences and the desired learning outcomes, that faculty implementing active learning engage students in discussion of learning theory and explain why the experiences that seem harder to students are designed to give them better learning outcomes and better prepare them for their future careers.

Finally, although programs are moving away from requiring a single collaborative project-based experience as a capstone or cornerstone project, there is still a limited range of opportunities across the curriculum for students to develop collaborative skills. While capstone projects can be highly effective, if it is students' first and only opportunity to work in groups, they are unlikely to know how to do so effectively. Additionally, having opportunities to reflect on and try different collaborative strategies will allow students to be better prepared for the workforce (e.g., Borge et al., 2018), which is not an option with a single project experience. As the field progresses, understanding more about how to foster collaborative learning skills early in an engineering program, and the manner in which scaffolding can be strategically removed as students become more adept at working in groups, is going to be important.

4.1 A Comment on Methods and Scope of the Research Reviewed

In this chapter, we brought together research from the fields of education and the learning sciences with research in engineering education. While there is significant overlap, the goals and methodologies of the two areas differ and make different types of contributions which should be acknowledged as we move forwards to consider the future work necessary in this field.

Historically, research in education and the learning sciences that describe collaborative learning focused on understanding the differences between individual and group performances, why groups differed in outcomes on the same tasks, and the types of interactions that are associated with successful learning. These studies are primarily grounded in constructivist and social constructivist theories of learning and draw on quantitative methods, such as performance comparisons between different configurations of learners or video analysis, and case study approaches to understand the nuances of interaction differences between groups. More recently, in the field of learning sciences, the
adoption of design-based research (Anderson & Shattuck, 2012; Bell, 2004) and especially design-based implementation research (Coburn & Penuel, 2016; Fishman & Penuel, 2021; Penuel et al., 2011) has focused on larger-scale studies that partner with educators to align research goals with the needs of practitioners. For the most part, this moves the work away from the more detailed analysis of interaction and more towards understanding the complex nature of classroom implementation. Cooperative learning, seen less in the field of learning sciences, had a more applied focus from the beginning. Grounded in social interdependence theory, researchers in cooperative learning quickly focused on designing classroom interventions and supporting teachers in effectively using cooperative learning in the classroom (Johnson & Johnson, 2009).

In contrast, engineering education research emerged from the needs of engineering practice, with research grounded in experimentation within classroom contexts and responding to the learning concerns raised by those embedded in the teaching. The resulting research tends to rely on classroom assessments, intervention reports, and survey data, although recent research tends to use a more comprehensive range of approaches. The research in this field is often more readily applicable in a new context, although less focused on the reported mechanisms behind the successes, making it harder to abstract and generalize across findings.

There does appear to be a move closer towards each other, with the maturation of the field of engineering education aligned with adoptions of research–practitioner partnerships and design-based implementation research in the learning sciences, which allow for approaches that seek to understand how questions of practice can be used to address theoretical questions about learning and collaboration, rather than starting with theoretical questions. However, there is still much to be explored in terms of what elements of intervention are truly necessary for success in different contexts.

4.2 Future Research

While there has been significant research conducted in the areas of collaborative and cooperative learning in engineering education, this review has highlighted key areas where it will be important to focus on future research.

4.2.1 Teams

There is a large amount of work that illustrates what groups look like when they are successful, particularly over short periods of time (Barron et al., 2009; Mercier et al., 2009). One important area where more research is needed, however, is exploring groups over long periods of time in order to understand how collaboration develops within teams of students and how best to establish and support teams as they negotiate learning over multiple sessions, weeks, or even semesters.

Furthermore, understanding the nature of the experiences of minoritized students is of paramount importance. The research that currently exists points towards a complex relationship between group learning activities and minoritized status. In particular, research that creates distinctions between different minoritized groups, rather than aggregating them as is common, is important to understand more about how different students experience group work. In addition, while research points towards the value for future collaborators of engaging with a diverse team, it is important to understand and mitigate the additional burden placed on minoritized students in managing stereotype-related expectations and acting as a representative for their entire group.

4.2.2 Tasks

The design of collaborative tasks that are effective for groups is one area where there is a need for a large amount of future research. In particular, it is important that we develop an understanding
of how to embed scaffolds within tasks for students to manage their own problem-solving processes, and how to fade those scaffolds over time to allow students to develop effective collaborative problem-solving skills when they face these problems in a work situation.

4.2.3 Tools

The potential for technology to support collaborative learning is just emerging, particularly as we learn more about how to use multi-modal data analytics to understand more about the nature of interaction and problem-solving processes (Paquette et al., 2018). This type of research holds the potential to gain more insight into the moment-to-moment development of shared understandings and the unfolding of collaborative interactions over time. It is also possible it will provide new ways to consider the quality of collaborative interactions and problem-solving. Once we have sufficient understanding of the elements of collaboration we can assess through indirect measures, such as screen activity, tone of voice, etc., we will be able to provide more targeted support for students and instructors. Initial versions of this type of work show promise (e.g., Paquette et al., 2018; Viswanathan & Vanlehn, 2018).

4.2.4 Teachers

Research on the role of teachers in setting up cooperative learning has always been important; however, it is only since the late 2000s that attention to the role of teachers during group activity has started to gain attention within the various fields attending to collaborative learning (Kaendler et al., 2015; Webb et al., 2019). There is much to be explored in this area – understanding the role of the teacher, how they should intervene in groups, and how to prepare people to use this form of pedagogy effectively.

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References


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