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Boundary interactions of applied physics and mechanical engineering students in a challenge-based learning course

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ABSTRACT

Higher engineering education programmes increasingly include courses characterised by real-world problems and student collaboration in multidisciplinary teams. Research findings demonstrate that students remain limited in perceiving and meaningfully bridging disciplinary differences in these course contexts. Drawing on the literature on boundaries and boundary interactions, this study sought to investigate how applied physics and mechanical engineering students managed their disciplinary differences in a challenge-based learning course. Using a qualitative, case study methodology, data from two multidisciplinary student teams ($n = 12$) were collected through reflective journals, individual interviews, and observations of team meetings. The findings confirm the value of disciplinary boundaries in creating new learning opportunities. The students coordinated their disciplinary differences during discussions in team meetings, preparations for the project plan and the stakeholder pitch, and test sessions in the lab. Results provide insights for designing similar courses and for future research.

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Boundary interactions; challenge-based learning; disciplinary boundaries; multidisciplinary teamwork

1. Introduction

To arrive at creative solutions to complex societal problems, it is essential to use concepts and methods of multiple disciplines (Schleicher et al. 2019). Recent reviews and reports on the future workforce notably describe the need for the collaboration of experts from different disciplines to play a role in addressing societal problems such as climate change and access to clean water (Accreditation Board for Engineering and Technology [ABET] 2021; Delisle and Lajoie 2022). Due to these world-wide necessities, higher education programmes often expect students to be able to recognise and use multiple disciplinary perspectives to solve real-world problems. These different perspectives can be arranged in courses with students of different engineering departments (Ludwig, Nagel, and Lewis 2017; Van den Beemt et al. 2020) or a combination of students of engineering and science majors (e.g. Henkel et al. 2015). These courses offer students authentic real-world problems and the opportunity to collaborate towards finding integrated solutions as a team (e.g. Vogler et al. 2018).

Despite the general positive assessment of teamwork by science and engineering students (e.g. Tan and Goh 2019), findings also show that failure to perceive and accommodate disciplinary boundaries leads to unintended outcomes such as boredom or frustration (Spelt et al. 2017). Also, it might lead to a division of tasks over collaboration (Cobb et al. 2008; MacLeod and Van der Veen 2020). At the disciplinary boundaries, ‘competence and experience tend to diverge’ (Wenger 2000, 233). When students recognise and act upon divergence, unique learning opportunities surface (Akkerman and Bakker 2011; Wenger 1998). Because not all student teams naturally create such learning opportunities, the literature can benefit from pedagogical suggestions on how to support science and engineering students in bridging disciplines (Akkerman and Bakker 2011; Henkel et al. 2015). There is a continuing need to identify and implement processes

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that can better support students' multidisciplinary teamwork practices (Feng et al. 2023; Izenberg et al. 2022). With this background, this study took a close look at the multidisciplinary teamwork by students coming from two disciplinary communities, applied physics (AP) and mechanical engineering (ME). We investigated successful boundary interactions in this challenge-based learning (CBL) course centred around control theory and application (Akkerman and Bakker 2011; Wenger 1998; 2000). In our previous work (Mesutoglu et al. 2022), we introduced pedagogical facilitators (e.g. team communication, tutor guidance, using individual presentations) of multidisciplinary teamwork in a CBL course. Findings also stressed a difficulty in communicating across disciplines to define and work on a problem. Building on our findings, we intended to understand team communication through the kinds of boundary interactions between groups of people (Wenger 2000). Focusing on student experiences can reveal what helps or hinders successful team communication (Vuojärvi et al. 2022).

Approaching an overarching challenge or a theme with the knowledge and methods of multiple disciplines lies at the core of CBL (Membrillo-Hernández et al. 2019). CBL courses, found most suitable for science, technology, engineering, and mathematics (STEM) majors, present students with authentic challenges that suggest reliance on different disciplines (Gallagher and Savage 2023). In line with its highly open-ended nature and limited guidance for student teams, we expect that CBL can provide a relevant setting to investigate boundary interactions. The questions that lead this research are: (1) what differences did AP and ME students recognise between their disciplinary communities in a CBL course? and (2) what boundary interactions emerged across the disciplines AP and ME during teamwork in a CBL course?

2. Conceptual framework

This section starts with a discussion of multidisciplinary teamwork in engineering education followed by a description of our conceptual background for boundaries. Then we explain our pedagogical framework, CBL, for the course design.

2.1. Multidisciplinary teamwork in engineering education

Higher engineering education aims to equip students with the workforce's highly demanded skills such as teamwork and effective collaboration across disciplinary boundaries. The difficulty in training students for these skills stems partly from structured curricula that typically segregate STEM subjects and focus more on content (Dorado-Vicente et al. 2020; Keenahan and McCrum 2021). Multidisciplinary teamwork offers an opportunity to tackle these shortcomings and to prepare students for professional life where dialogue across disciplines is increasingly sought (ABET 2018). Teamwork of engineering and science students usually takes place in capstone courses, problem-based, design-based, CBL courses, and other courses that use knowledge and methods of multiple disciplines in their design (Keenahan and McCrum 2021; Membrillo-Hernández et al. 2019).

Multiple terms including multidisciplinary, cross-disciplinary, and interdisciplinary are used to describe team interaction in engineering education (e.g. Borrego and Newswander 2008; Ludwig, Nagel, and Lewis 2017). Multidisciplinarity in this study is defined in line with the descriptive review findings of Heikkinen and Isomöttönen (2015): students of engineering and other disciplines working together as a team on an open-ended real-life problem. Like the reasoning of Ludwig, Nagel, and Lewis (2017) for multidisciplinarity, our focus is not on the integration of disciplines, rather on exploring how students learn to recognise differences and contribute to teamwork using these differences.

Research frequently found evidence for science and engineering students' perceived difficulties practicing negotiation and creating bridges between disciplinary boundaries (e.g. Sharma et al. 2017; Spelt et al. 2017). Exemplary difficulties are failing to understand the existing language and routines of team members and to identify tasks that match the disciplinary expertise (Borrego and Newswander 2008; Jensen, Utriainen, and Steinert 2018; MacLeod and Van der Veen 2020). Differences in prior knowledge concerning the given challenge can cause difficulties in collaboration in a CBL course (Mesutoglu et al. 2022). Investigations into examples of successful boundary interactions can address the difficulties by suggesting further pedagogical cues.

2.2. Boundaries and boundary interactions

This study considers boundaries between disciplinary communities and boundary interactions as learning assets. Boundaries can be conceptualised as the differences that exist between social learning systems; groups or organisations (Akkerman and Bakker 2011; Wenger 2000), for example, between school administrators and university supervisors (Montecinos, Walker, and Maldonado 2015) or between discipline structures with shared knowledge and routines (Oborn and Dawson 2010). Although boundaries can naturally be expected due to the segregated systems of higher education, contributing to students' capabilities to connect disciplines is now part of the agenda of many universities (Vuojärvi et al. 2022).

New experiences, in our case multidisciplinary teamwork, force communities to revisit their existing competences for learning to take place (Wenger 1998; 2000). In the context of these new experiences, communities also realise the unique competence of each other. Once these differences, boundaries, are recognised, it is imperative to create bridges across boundaries. The purpose of bridging disciplinary communities during teamwork is to appreciate diversity and to acknowledge that as a learning opportunity (Vuojärvi et al. 2022). The bridges can come in the form of brokers, objects, and interactions. This study focuses on the ongoing interactions among people of different disciplinary communities (Akkerman and Bakker 2011; Montecinos, Walker, and Maldonado 2015; Wenger 2000).

Wenger (1998; 2000) presented three dimensions to understand to what extent communities are bridged in meaningful ways: coordination, transparency, and negotiation. *Coordination* refers to deliberate joint activities. Team members are expected to produce new ways of accommodating each other's shared disciplinary knowledge and routines without 'burdening others with details' (Wenger 2000, 234). This might especially be difficult when there is not much clarity on roles and responsibilities (Montecinos, Walker, and Maldonado 2015). The coordinated knowledge and/or routines across disciplines should be well-defined and be interpretable into action. An example is a joint problem-solving session.

The fact that experts from different disciplines do not grasp each other's perspectives links to *transparency*, the ability to understand the practices of one another. Transparency underlines access to the meaning of practices involved in relation to a community's routines, norms, accumulated knowledge and making that visible, thus transparent, to others. Finally, *negotiation* describes a balanced appreciation of the disciplines without enforcing ways of doing; having two-way communication. The opposite will 'reinforce the boundary rather than bridge it' (Wenger 2000, 234). The joint activities earlier mentioned for coordination are expected to surface and negotiate the unique disciplinary perspectives.

As the consideration of multiple knowledge disciplines is a core attribute of CBL, we will zoom in on what this entails in CBL teamwork. Arranging team meetings and other discussion moments in CBL courses provide the students in such teams with space for collaboration across disciplines. Because students are expected to understand the challenge and then work on their problem as a team, acquiring the skills to understand one another and bridge boundaries becomes essential (Jensen, Utriainen, and Steinert 2018; Kohn Rådberg et al. 2020).

3. Pedagogical framework-CBL

CBL highlights opportunities for multi- and inter-disciplinary teamwork (Gallagher and Savage 2023; Van den Beemt, van de Watering, and Bots 2023). In teams, students ask questions and formulate ideas to address a challenge that should be constructed in a way that relates to students' previous experiences and that can result in multiple solutions (Clegg and Diller 2019). CBL is interpreted as a progression of project-based learning along with some novel characteristics including a focus on open real-world problems, teamwork of students from different backgrounds, and collaboration with internal or external stakeholders (Jensen, Utriainen, and Steinert 2018; Kohn Rådberg et al. 2020; Malmqvist, Rådberg, and Lundqvist 2015; Van den Beemt, van de Watering, and Bots 2023). CBL aligns well with and supports the Conceiving, Designing, Implementing, Operating (CDIO) framework.

Conceptualising CBL to clarify its operationalisation, Van den Beemt, van de Watering, and Bots (2023) introduced three dimensions: (a) vision, (b) teaching and learning, and (c) support as shown in Figure 1. Adopting these dimensions starts with formulating the goals to offer the context to the students and choosing a complex challenge from real life that addresses these goals.

Figure 1. Dimensions and indicators of CBL (Van den Beemt, van de Watering, and Bots 2023, 4).

Student teams collaborate with challenge owners; internal or external stakeholders. While an open problem with real external stakeholders might resonate with extra difficulties for students to identify meaningful tasks for everyone in the team, it can at the same time facilitate higher levels of creativity and diversity (MacLeod and Van der Veen 2020; Yang et al. 2018). Students get the opportunity to consider a range of perspectives from all team members as they address the challenge (Clegg and Diller 2019).

With an open-ended challenge, students are encouraged to deepen their own disciplinary knowledge in addition to meaningfully bringing together different disciplines in teams. Self-directed learning is facilitated through students' formulation of their own problems. Through the processes of problem formulation and design of solutions, higher-order skills such as creativity, innovation, and critical thinking are stimulated. The framework also underlines a balance between openness and scaffolding. For this reason, it is recommended for the teachers to undertake different roles, for example, coach or co-learner (Van den Beemt, van de Watering, and Bots 2023).

4. Case study description

A second-year bachelor course, CBL Systems and Control Project, was created with one of its curricular goals to bring together AP and ME students. This was the second implementation of the CBL course from our earlier work (Mesutoglu et al. 2022) with a different student cohort. The courses were motivated by the CBL vision of the university and its need for understanding multidisciplinary teamwork in CBL courses. Our AP and ME bachelor programmes include core theory and skills courses, capstone project courses, and options for electives. In many of these courses, students receive CBL assignments. The course described in this research is one of our few multidisciplinary CBL courses and the first that brings together students from the AP and ME programmes.

The goal of this study was to investigate the context of multidisciplinary teams of AP and ME students in a CBL course; the differences recognised by the students and the interactions that bridged the disciplines for team benefit. CBL entails interactions between students from (sub-)disciplines, but a number is not suggested for the disciplines to be represented. According to the CBL compass (Van den Beemt, van de Watering, and Bots 2023), the team composition can range from 'not implemented' to 'fully implemented' taking into account the nature of the challenge. Furthermore, there are example teams with less than three disciplines in CBL (Membrillo-Hernández et al. 2019) and in other similar multidisciplinary engineering courses (Hotaling et al. 2012).

The CBL course ran for nine weeks. The students engaged in: (a) common sessions, (b) laboratory sessions, and (c) two multidisciplinary team meetings per week to work on the design challenge: 'control and optimise a pick and place sorting system (robot) for a hypothetical customer'. As part of the introductory presentations of the first week, the external stakeholder gave information on their assignment and their worked cases. This was a company developing pick-and-place robots for warehouses among others. A training session was implemented during the second week on time management and collaboration. On the third week, during a field trip to the stakeholder company, the student teams pitched their 'project plans' and received feedback. On the final week, the teams presented their progress and how their experiments were translated into a prototype via a video and a poster. After feedback rounds, the teacher team and the stakeholder announced a winner, based on scientific rigour and potential usefulness.

The face-to-face team meetings of one hour took place twice a week during the first eight weeks of the course with participation of all members and a tutor for each team. The meetings included discussions and knowledge sharing on current progress, reflections, and decision-making on the issue at hand (e.g. problems with image detection), interim presentations of team members to share any results, and tutor feedback. Besides the meetings, the teams did experiments in the lab using the robot arm and their laptops with participation of agreed-on team members.

The course studied in this research was designed in line with the three dimensions of CBL (Van den Beemt, van de Watering, and Bots 2023) (see Figure 1). Stemming from the open-ended nature of the challenge, the student teams were flexible in choosing their hypothetical customer e.g. a food warehouse, a post order sorting station, or web shops. The external stakeholder from the industry was involved mainly to collaborate with the teams in idea generation. The extent of stakeholder collaboration in a CBL setting can reflect a full collaboration where the challenge requires continuous interest and involvement. In our case, the collaboration of the stakeholder was limited to choosing, introducing, and supporting the challenge (Van den Beemt, van de Watering, and Bots 2023). The course learning outcomes highlighted applying knowledge on dynamic behaviour, signals, and systems and control. Activities such as working with the robot arm, experimenting, and running simulations provided context for students to apply fundamental knowledge and skills.

The field trip to the stakeholder company and receiving feedback through a pitch addressed problem formulation and the design process. Tutors recruited from the master student's population in AP and ME attended all team meetings and provided scaffolding. Course technologies included a course learning management system, Canvas, Microsoft Teams channels separate for each team, and a robot arm set-up in the lab with camera, vacuum gripper and conveyor belt, software interfaces that connect the hardware to object detection software, Matlab, and Simulink. Course assessment reflected a balance between individual (peer review, reflection report, interim team presentation) and team measures (project plan, poster, and video) and between formative and summative assessment techniques. A team of AP and ME teachers collaborated at all stages of the design and implementation of the course. One of the teachers more experienced in CBL pedagogy provided guidance in overseeing CBL characteristics (Van den Beemt, van de Watering, and Bots 2023).

5. Method

5.1. Research design

This research employed a qualitative instrumental case study useful in understanding how a certain social phenomenon occurs, providing an in-depth description. Case studies are grounded in contemporary events that the research has no intention of controlling and rely heavily on converging a set of research evidence (Yin 2014). An instrumental case study was found useful as the goal was to study multidisciplinary teamwork in a CBL course. The CBL course at a public university was identified as the unit of analysis and the two multidisciplinary teams were treated as sub-cases (Merriam and Tisdell 2015; Yin 2014).

5.2. Participants

This course is part of the second-year programme of AP and ME. All students had the opportunity to either take this multidisciplinary pilot course or its original version, a monodisciplinary course, within their programmes on the same topic. In total, 18 students wrote motivation letters to take this multidisciplinary course. Among them, four were AP and fourteen were ME students. The teachers could only form two multidisciplinary teams which constituted the sub-cases for this study. Each multidisciplinary team included two AP and four ME students.

All students had teamwork experience from their previous courses. They have experienced multidisciplinary teamwork in a mandatory engineering design course. In addition, the ME students were enrolled in multidisciplinary design-based learning courses. AP students had taken experimental courses where they prepared and conducted lab experiments. All students had enrolled in theoretical courses on some of the knowledge that could be applied in this pilot course. The fact that AP and ME students had different experiences; with regards to type and frequency of teamwork, laboratory experience, and previous disciplinary courses, enabled us to treat them as separate disciplinary communities (Wenger 2000).

5.3. Data collection

The research was approved by the university Ethics Committee. All participants, 12 students and one tutor, individually signed informed consent forms. Figure 1 summarises the timeline for data collection. In line with case study research, this study used multiple data collection strategies: 'reflective journals', 'individual interviews', and 'observations of team meetings' (Yin 2014). Data collection was spread over the six weeks of the course to be able to study the multidisciplinary teams in different stages: problem definition, planning, experimenting, and presenting results. The reflective journals and the interviews constituted the main qualitative data. The task of writing reflective journals included some questions regarding teamwork experiences. In interviews, we also prompted students to give their evaluation of their teamwork across disciplines. Questions on the journal and the interview protocol went through minor revisions after receiving expert opinion from the teacher team and from an external researcher.

5.3.1. Reflective journals

Three times through the course, the students of the two multidisciplinary teams ($n = 12$) were asked to fill in reflective journals (see Figure 2). Data collection was announced on the three separate times on course Canvas with a corresponding Google forms link. The students were given a two-day deadline to respond. In the three implementations, 12, 10, and 8 students participated respectively.

The journals also asked for students' disciplines. All journal implementations consisted of the same set of four open-ended questions: '(1) when you think of the academic and personal skills or knowledge you gained in the past two weeks/this week; how do you think this learning occurred? (2) please describe your collaboration and decision making with the student(s) of the other discipline in your team, (3) in your team, were the disciplinary competences (e.g. knowledge, point of view, methods) introduced and interacted? If so, how? and (4) what activities and/or discussions that bring together the disciplines do you consider to be successful?'. The use of reflective journals made it possible to engage students in self-reflection and gave them the space to express their experiences on a regular basis (Heikkinen and Isomöttönen 2015).

5.3.2. Interviews

Interviews were individually conducted with the volunteering 10 students of the two multidisciplinary teams and with one volunteering tutor. Interviews of 30 min on average were conducted online via Microsoft Teams. The interview protocol contained broad open-ended questions on the collaboration between AP and ME students such as 'can you discuss to what extent in your opinion there was multidisciplinary collaboration between AP and ME students?' and 'do you agree that in general, your team took action using the knowledge, practices of the two disciplines, can you explain your response?' There were also more specific questions to target differences and boundary interactions: 'can you think of activities that brought together

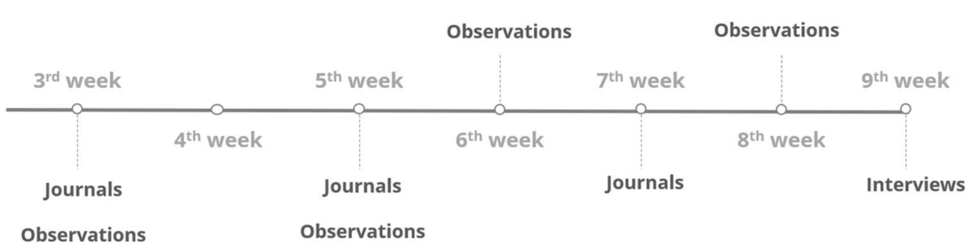

Figure 2. Timeline for data collection.

the two disciplines (closer)?' and 'what were some instances of joint activities or discussions where disciplinary differences surfaced?' All interviews were audiotaped.

The journal and the interview data complement each other in that the journal data focused on experiences around regular time points, whereas the interview data reflected a general evaluation of the course period.

5.3.3. Observations

The third data collection strategy was observations of the weekly multidisciplinary team meetings. Non-participant observations were conducted to confirm or disconfirm the main qualitative data. Specific incidents such as discussions between AP and ME students could be captured (Merriam and Tisdell 2015, 138). The students' verbal exchanges were collected using video recorders at four points in time from both teams (see Figure 2). The lead researcher took field notes documenting moments of multidisciplinary discussions. Exhibiting a firsthand encounter with multidisciplinary collaboration, observations were used as a complementary source to include the interactions between AP and ME students in its natural setting.

5.4. Data analysis

The initial step was transcribing the audio and video recordings. Next, the lead researcher performed editing as she listened to and watched the recordings while simultaneously examining the transcripts created by Microsoft Teams.

The further steps were derived from the 'step-by-step process' by Merriam and Tisdell (2015, 204) using Atlas.ti. The software helped to ensure important codes are not ignored (Weitzman 2000). First, the researchers read the transcripts and journal accounts several times to have a general understanding and to highlight potentially interesting and relevant pieces of the data. Then the data was examined through the perspective of the conceptual framework to understand patterns within and across different types of data. In the first rounds of this *open coding,* emerging codes were not yet mutually exclusive. In the next rounds, going back and forth between the conceptual framework and the main qualitative data, the recurring codes could be distinguished and finalised under the two categories: 'differences that the students recognized' and 'descriptions for bridging the disciplines'. The final part was assigning solid codes to the bulk of data. Atlas.ti offered a means for frequency queries, identification of better pieces of relevant data, and creation of graphical networks. A complete response or a section of a response participants provided were assigned with codes. Percentages referred to the appearances of the coded quotes; percentage of a code represented the proportion that the code was assigned amongst the total frequency for all assigned codes. The video transcripts were analysed to confirm and to further demonstrate the codes. Using direct quotations from the video recordings in conjunction with the main qualitative data was useful in presenting thick descriptions (Yin 2016). A single case description was written to portray the single case of 'multidisciplinary teamwork of AP and ME students in a CBL course' (Yin 2014).

Triangulating reflective journals and interviews with observations as diverse data sources contributed to the trustworthiness of our findings, more specifically to the criteria of dependability and confirmability. Researchers' prolonged engagement with the data, researchers' collaborations in creating and assigning codes in iterative cycles, weekly meetings with the teacher team with the participation of the lead researcher helped to establish credibility. Randomly selected sections of the interview transcripts and journal responses, 10 pages in total, were used to assess inter-rater reliability. By means of percentage agreement, an acceptable score of .78 (Miles and Huberman 1994) was calculated among two of the researchers.

6. Results

The results are presented in two sections in line with the research questions; 'differences that the students recognized' and 'types of boundary interactions'.

6.1. Differences recognised between AP and ME students

The three boundary areas in which students identified differences were: (a) teamwork skills, (b) project management practices, and (c) theoretical knowledge.

6.1.1. Differences in communication and teamwork skills

The results indicated that AP students realised not having sufficient skills to act during the structured weekly team meetings and had to take on unfamiliar roles. An AP student, for example, reported: ' … the meetings were very different from how I was used to … I learned the most in that area by being chair and how to really lead a meeting or how to act in the meeting'. ME students frequently described their background in practicing structured team roles, e.g. chairman, minute-taker, referring to their prior coursework, mostly to design-based and also to the engineering design course. An ME student expressed: ' … an AP student set to be a chairman for one of the meetings … that was quite terrible … he didn't have any experience on it'.

AP students also had to learn to express individual ideas and progress more effectively during team meetings. The following two quotations are from ME students:

> ME students were a little better in meetings … discussing things quickly and concisely and making stuff clear and making decisions' and 'AP students had a bit of trouble, communicating what they had done and selecting the information that we need to know and that we don't need to know.

An AP student discussed that, creating action points at the end of each meeting facilitated expressing what had been done in between meetings. At the same time, this difference also created a learning opportunity for ME students to deepen their teamwork skills: 'One of them had a lot of trouble understanding ME approach. So, being in between that and trying to get AP students to communicate well, that was a learning opportunity for me.' Another ME student explained that asking clear questions was a strategy to facilitate AP' students' communication: 'At the start it was quite difficult to communicate with him because you had to ask very specific questions and then he will tell you'.

6.1.2. Differences in project management practices

Results revealed that the students recognised differences in how they approached project management. Project planning and organisation was strongly felt as an AP contribution and as a learning opportunity for ME students: ' … the AP students contributed most through planning and organization, but also to keep everything connected and keep the goal in mind'. The students sensed that AP students facilitated the teams' capacity to keep the overview, to notice alternative scenarios, and consider mitigations. Results show that one of the course assignments, the project plan, put forth AP students' experience in creating and writing plans. An AP and a ME student respectively reported:

> … when it comes to the measurement plan, thinking of all the things you have to do for that thing, that's where the AP came forward most' and ' … AP students have more knowledge on formulating a very good and constructive plan containing all the necessary details.

AP and ME students offered unfamiliar perspectives to each other in that AP students wanted to manage planning mainly by paying attention to unknowns before any experiments whereas ME students wanted to plan based on outcomes of empirical trials. This was illustrated by the tutor: 'AP students tried to investigate why things are like they are. So I think that part is really their contribution to the project'.

The students believe that it was more often the case that they coordinated this difference as opposed to being experienced as troubling:

> The AP students were like … what is the physical meaning behind transfer function, bode plots etc … .? Because they really thought of everything like that and that really made me understand the setup better because I really had to think like, what am I actually doing?

This difference was also experienced in responding to immediate problems students faced in the lab working with the robot arm as reported by an AP and a ME student respectively:

> We were in an experiment and we ran into some errors … for me it felt natural to take a step back and investigate … But for the ME student that I was working with at the moment, he wanted to try out a bunch of different things immediately and hope that they work

and again a learning opportunity was reported: ' … during the test sessions … I think there you learn to collaborate with the multidisciplinary team, but you also learn to see … mainly each other's approaches to problems you face'.

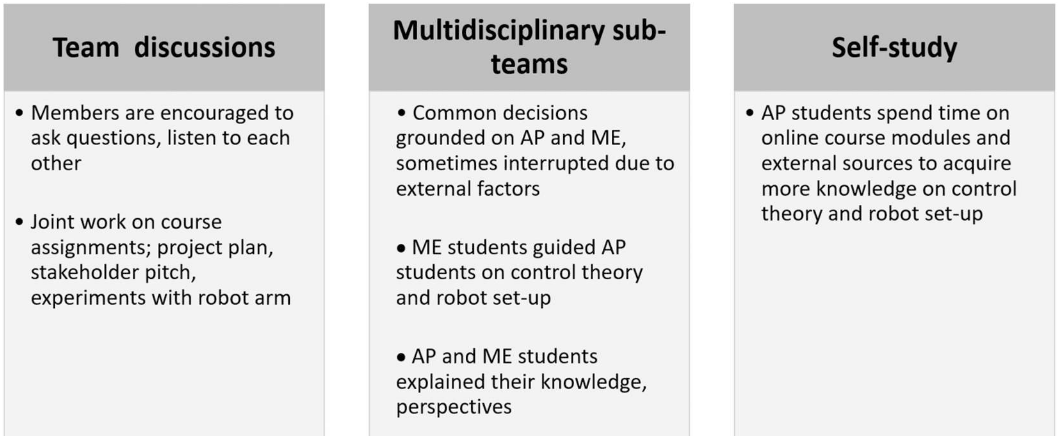

Figure 3. Summary of how students overcame or negotiated disciplinary differences.

6.1.3. Differences in theoretical knowledge

The course content was mostly new to AP students; thus content-wise the course was perceived to be more of an unfamiliar space for the AP students. An exemplary response from a ME student was: 'ME students were just very strong in understanding the material because we've had courses on control systems before. We knew better how to apply our theoretical knowledge to the actual setup'.

Working in the multidisciplinary team was beneficial for AP students' learning of new theoretical knowledge. Results also show that AP students were less active in team meetings and during lab sessions in the earlier weeks of the course, until they acquired sufficient theoretical knowledge to work on the assignment:

> … during testing, the AP students felt a bit more silent in the beginning … a bit anxious, maybe breaking the robot or something because they were very careful with everything and we just plugged everything in and we tried to set it up and stuff.

6.2. Boundary interactions of AP and ME students

Figure 3 summarises the three types of interactions that emerged to coordinate the expertise of the disciplinary communities.

6.2.1. Organising multidisciplinary discussions during team meetings

We found that the AP and ME students managed to bridge their disciplinary differences at the team level in multiple ways. In one of the organised discussions during the weekly meetings, students worked on the project plan, bridging AP students' approach to project planning and ME students' knowledge on control theory. A ME student expressed: 'ME have more background knowledge on the controllers and dynamics/ control system. AP do have more knowledge on formulating a very good and constructive measurement plan containing all the necessary details. This was useful … .' Because the teams had not seen the robot set up until submitting the plan, ME students nicely contributed with their prior knowledge on the topic and the robot set-up. An illustrative episode from the observations can be found in Table 1.

Table 1. Episode illustrating a planning discussion.

Turn	Student utterances
AP-1	… planning is very hard to do without actually making the experiment … . we used to do it while doing the experiment … .This is like making it before. That's why it might be confusing when you read it (*the plan*) and it because it's very hard.
ME-1	Maybe we can prioritise stuff to make decision making easier.
AP-1	Do you want to see five objects in a row on the conveyer belt? And then the camera can detect? (*asking to ME students*)
ME-2	That still needs to be measured, because that depends on, for example, the suction power versus the friction, because there will be a limit where the boxes cannot be pushed anymore and the suction cup just releases because it doesn't have enough power. So that needs to be measured. That's why I wrote that … ..like quality control …

Table 2. Episode illustrating task division.

Turn	Student utterances
AP-1	I think for ourselves … the specifics could be useful … ..*(while making the pitch slides)*
AP-2	Yes, for ourselves.
AP-1	Then we explain what we plan to do. They could say: 'have you tried this method, this might be better'.
ME-2	So maybe you can have a slide with technical feasibility that says, it's got like some graphics three blobs, three circles, one of them is blob analysis. One of them is control design. One of them is something I'm forgetting right now. Just like a breakdown of the steps that we're gonna do.
AP-1	The chronology of what you're saying, I'm creating them.
ME-2	Yeah, if there is something that needs to be cleared up (*to AP students*), feel free to stop the meeting.
ME-3	Who's presenting?
AP-2	I can always do it. I'm not an expert on the content yet because we do focus on the planning … .

A second team-level discussion targeted the stakeholder pitch using AP students' focus on the overview and the details and ME students' content knowledge. An illustrative episode from the observations in Table 2 illustrates team progress.

The teams also discussed concerns and disagreements that emerged in between meetings. During a discussion on state flow in both teams, disciplinary differences were negotiated. A ME student reported in his journal: 'one of the most memorable multidisciplinary discussions were about prioritizing control of the robot movement or prioritizing the state flow'. Both teams in the end agreed on ME students' recommendation to prioritise the robot arm, considering time constraints. This meant having something that works even though not so smooth, as opposed to more research and more test results to get a smoother movement, which was recommended by the AP students. An example episode from the observations is presented in Table 3.

The results showed that both teams strived for consensus when making decisions during the discussions with different positions of AP and ME students: ' … it does lead to interesting discussions. Overall decision making went in conversation with everyone' and 'because there were quite a few eye-opening moments for me as well where AP students during the meetings just mentioned something that we completely missed and then I could think about it and account for that situation'.

6.2.2. Working in multidisciplinary sub-teams

Students coordinated disciplinary differences also at sub-team levels. The teams first identified action points and then assigned AP and ME students to sub-teams to work together until the next meeting. These included tasks such as working together on the project plan or experimenting in the lab with the robot arm (e.g. working with the camera, and coding scripts in Matlab and Simulink). A ME student described: ' … depending on the experiment and the goals we set per week, we made sure to distribute tasks equally. So we get both standpoints'. It is reported several times that working with the robot arm in the lab sessions connected disciplines, e.g. ' … practical sessions at the robot bring together the disciplines' and 'I cooperated with one of the AP students and it was very smooth and efficient. The educational background differences brought up a fresh perspective on some things'.

A ME student described a conflict with an AP student in the lab which was later resolved in another sub-team meeting:

Table 3. Episode illustrating multidisciplinary negotiations.

Turn	Student utterances
ME-1	I have everything about state flow clear. We shouldn't go too much into the technical stuff.
AP-1	I think loop shaping should have quite high priority because it will be data processing, transfer functions and write the action points after that it's already the finishing controls … before we can even use the state flow, basically we have to have our loops or our controllers done … before we can actually implement everything we need to have the controls tested.
ME-2	You can do research and that's fine, but then you have to convince all of us with that knowledge and stuff.
AP-1	We started some initial values … I think with the robot arm we need the precision and we need as little overshoot as possible
AP-1	Do we actually also want to do the measurements for the vacuum gripper that we can do the transfer function for that as well?
ME-3	The transfer function is only meant to optimise it, right? And optimising is the last phase of this project. Don't see why we would want to really carefully. Maybe later on in the project, if you're like all we want to save energy or something or … ..
ME-3	Yeah, for now it's a low priority.

… last week I had a hard time agreeing with the AP students because of the lack of communication … . we decided to meet one-on-one and discuss the pro's and cons together, in a quiet space. This really helped to understand each other and come to a decision together.

Another ME student explained the role of external course factors in bridging disciplines sometimes difficult to handle:

it just creates a bit of friction sometimes … because there were so many external factors playing a role, like broken robots, the stress of the quarter ending. You have these different approaches and you're both very sure that that's the correct one. And then you're like, I think we need to do it this way … it was sometimes a bit difficult.

During team meetings and work in sub-teams, AP and ME students opened-up their disciplinary communities to each other; asking questions and explaining their knowledge, practices, and routines. An AP and a ME student expressed: 'I could discuss with the other four ME students and some of them even took the time to teach me, really just to answer my questions. My understanding of those topics improved a lot' and ' … that is something where the AP students were not very comfortable with yet, because they had no idea what a phase margin or anything like it was. So we really had to guide them'.

Results showed students' interest in understanding each other's perspectives: 'We were always open to other opinions, so the ME student is always asked, why do you think this or that? Also AP students tried to explain as best as they could … .the skills they had on the topics'.

6.2.3. AP students' self-studying on control theory

A third practice was AP students' studying the course topics that were unfamiliar to them. Results show that AP students spent time mainly on the online course modules to acquire the necessary knowledge on control systems and the robot set-up. An ME student explained:

… especially towards the end of the project, we had to focus a lot more on the technical side of things and AP students did an amazing job learning new subjects that were completely new to them and they just helped out as they could.

One AP student made time to locate and use an external source for his learning and team benefit: ' … one of the AP students took a 10 hour training for the software, for example, to get to know it'. ME students' explanations were also helpful in widening AP students' knowledge: 'keep up at our knowledge regarding the control systems and I do think during meetings we also spend some time on explaining them'.

7. Discussion

Responding to the need to improve collaboration across disciplines in teams of engineering and science students (Cobb et al. 2008; Spelt et al. 2017), our findings show that the students indeed experienced boundaries. The identified boundary interactions demonstrate success in bridging the disciplines and continuing with the project as opposed to discontinuity in action (Akkerman and Bakker 2011; Wenger 2000). Identified activities to bridge the differences include team discussions, negotiations, and smart ways of organising tasks. Thus, the results suggest that recognising and managing boundaries allows for unique learning opportunities (Akkerman and Bakker 2011; Van den Beemt, van de Watering, and Bots 2023; Vuojärvi et al. 2022; Wenger 2000).

7.1. Differences recognised between AP and ME students

Structured team meetings with clear team roles were new to AP students, while ME students had this experience in their former courses. Because communication and teamwork are of high priority for physics and engineering students to prepare for professional life, clearly this course offered learning opportunities for both AP and ME students. The teams learned to include AP students more, by having them practice the member roles and by asking them questions during the meetings. AP students improved their presence at the team meetings also by learning about control theory and its applications on the robot arm as the course progressed. This was achieved by receiving guidance from ME students, spending time on course materials and other online resources. Because AP students had taken less courses relevant to the course content, a larger part of the course topics was entirely new to them. Gaining the necessary background is important in that, only after acquiring a common ground, all members are more present (e.g. Oborn and Dawson 2010). Suggestions to facilitate this within limited course timelines include providing extra scaffolding to explain unclear parts of the content, balancing team composition, and promoting new learning activities to foster recognition of disciplinary expertise (Heikkinen and Isomöttönen 2015; Wang et al. 2010).

From the CBL perspective, findings might also relate to difficulties multidisciplinary student teams experience in defining a problem across knowledge domains (e.g. Kohn Rådberg et al. 2020; Pearce 2019). Jensen, Utriainen, and Steinert (2018) revealed team dynamics in CBL environments as a factor to decrease the potential of using all knowledge domains in multidisciplinary teams while our findings evidenced a positive and supportive team environment with transparency. Our findings also revealed AP students' experiencing an unfamiliar space when it comes to engaging with new content knowledge. Taken together, it might be argued that ME students could experience a knowledge boundary if AP students were more active in team meetings during the initial weeks of the course. This then could result in identification of a problem more compatible with AP background knowledge. The openness in problem formulation might have made it difficult for students to recognise the specialised disciplinary knowledge they had gained until this course (Kohn Rådberg et al. 2020). Formulating a problem considering multiple disciplinary backgrounds is essential for CBL and students can progress in doing that with practice (Kohn Rådberg et al. 2020; Pearce 2019).

Previous literature document the importance of problem formulation in CBL settings and strategies revealed as beneficial. Jensen, Utriainen, and Steinert (2018) showed that redefining the problem that the multidisciplinary team is solving and grasping the external knowledge necessary were ranked as relatively more difficult design tasks. It can also be that the STEM student teams might need more time to gain the ability to realise the difficulty and the value of defining a problem across disciplines and to frame the common problem (Kohn Rådberg et al. 2020; Ludwig, Nagel, and Lewis 2017). Previous research suggest frequent dialogue meetings with the stakeholders, strong involvement and supervision from the teachers of the multiple disciplines, teachers taking on different roles (e.g. coach, co-learner), and a challenge topic closely related to all team members (Clegg and Diller 2019; Costa et al. 2019; Jensen, Utriainen, and Steinert 2018; Van den Beemt, van de Watering, and Bots 2023). Clegg and Diller (2019) recommends 10-minute challenge prompts for multidisciplinary teams to practice identification of problems and relevant domains where knowledge will be necessary. Asking students about their potential disciplinary contributions earlier in the course and reflection sessions where students discuss different disciplinary perspectives and contributions can further assist teams (Jensen, Utriainen, and Steinert 2018; Richter and Paretti 2009).

Recognising differences in engaging with problems in multidisciplinary student teams encourages students' thinking of learning in new ways and enlarges their problem-solving toolbox (Kohn Rådberg et al. 2020; Wang et al. 2010). Like our findings, Jensen, Utriainen, and Steinert (2018) revealed that the multidisciplinary teams recognised the differences in perspectives during the testing and building phase; some students were more interested in research and further thinking whereas others focused on building. Oborn and Dawson (2010) also note that the differences in problem-solving approaches were explicit mainly during test sessions due to multiple immediate problems arising.

7.2. Boundary interactions of AP and ME students

The revealed boundary interactions are indications of students' engagement in productive tension which offered new perspectives, and finally new ways of doing things. The students, in an open-ended CBL context, could recognise and use the differences of the disciplinary communities.

The AP and ME students were *transparent* to each other, questioned each other's assumptions, and explained their knowledge, perspectives, and routines (Oborn and Dawson 2010; Wenger 2000). They created the space to practice *coordination* and *negotiation* across boundaries during the weekly team meetings and in smaller teams of AP and ME students. The students connected the two disciplines in the earlier weeks of the course interacting on the assignments; 'project plan' and the 'stakeholder pitch'. Such concrete tasks support multidisciplinary teams in acknowledging differences and aligning coordination (Oborn and Dawson 2010; Wenger 2000). Although the difference between AP and ME students' knowledge on control theory and its applications on the robot arm caused confusion and disconnection for AP students at first, this situation did not lead to separation. AP students' competence in project planning e.g. keeping the overview, paying attention to details, unknowns was used for team progress and connected with ME students' conceptual knowledge (Costa et al. 2019; Lutsenko 2018). The team meetings and working in smaller multidisciplinary teams revealed the differences between how disciplines work and solve problems. The previous literature confirms engineering students' resorting to trial and error and intuition in problem solving (e.g. Garmendia, Guisasola, and Sierra 2007). This previously stemmed from, for example, not having the necessary knowledge and experience base (Gustafsson, Jonsson, and Enghag 2015). This type of a problem-solving strategy might not always lead to deeper comprehension even though the solution is correct in the end (Garmendia, Guisasola, and Sierra 2007). In developing a thinking programme for engineering students, Tan (2006) highlights elimination of 'erratic trial and error behaviour' which is fully impulsive. Our findings also confirm ME students' prioritising efficiency in solving problems (Richter and Paretti 2009). This also related, in our case, to time constraints and whether students believe that extra time for research and a full analysis will benefit their learning (Krishnan, Gabb, and Vale 2009). Physics students on the other hand, have a stronger inclination for applying a 'scientific approach' to problem solving; with a primary focus on how concepts are related (Zewdie 2014).

The teams using AP students' perspectives on project management also can be approached from different aspects. First, science students' as well as other non-engineering students' (e.g. arts) contributing to multidisciplinary teams with engineers with their expertise in writing plans and technical reports, being attentive to details is reported in the literature (e.g. MacLeod and Van der Veen 2020; Wang et al. 2010). This might have stemmed from physics students' experience in experimentation and documentation in their coursework and their interest in detailed arguments and analysis in writing (Kozminski et al. 2014; Wang et al. 2011). Complementary to this, the course learning outcomes and the topics being related to control theory together with the struggles students usually experience in problem identification in CBL courses might have let the teams not to spend too much effort on identifying a problem that would address AP knowledge (Yang et al. 2018). This result can also be explained with AP students' high level of tolerance with ambiguity as they were willing to leave their comfort zone and to learn new topics (Spelt et al. 2017). Experiencing these differences is important in that developing project management skills is part of engineering students' working methods (Costa et al. 2019). Overall, as a team, the students showed the ability to make an effort to catch up and understand the knowledge and practices of one another, illustrating *transparency* (Wenger 2000).

The teams interpreted differences into action on joint tasks, with an inclination towards collaboration over reinforcing boundaries or resistance to sharing knowledge (Krishnan, Gabb, and Vale 2009), suggesting good examples for *coordination* and *negotiation* (Wenger 1998; 2000). For CBL, multidisciplinary meetings provide the space for student teams to experience deeper levels of collaboration across disciplines (Kohn Rådberg et al. 2020; Van den Beemt, van de Watering, and Bots 2023). Results demonstrate that AP and ME students continued to be resources for each other during the later stages of the course through organising discussions during the meetings on emerging issues and as experimenting with the robot arm in cohorts of AP and ME students. AP and ME perspectives and more specifically, approaches to problems solving interacted often during these contacts (Holzer et al. 2016). Assigning tasks to sub-teams made the students work closer in testing and appreciating the value of communication across disciplines. Sub-teams also provide team meetings with relevant discussion points to facilitate the exchange of disciplinary knowledge and perspectives (Meah, Hake, and Wilkerson 2020). Discussions during team meetings and in sub-teams as opposed to splitting tasks up individually supports teams effectively in problem solving and understanding each other (Ludwig, Nagel, and Lewis 2017).

Another consensus was that sometimes due to course factors e.g. timeline demands and technical errors, grounding decision-making on both perspectives became difficult. As recommended by Vogler et al. (2018), additional scaffolding on interdisciplinary collaboration and explaining to the students the importance of ongoing cross-disciplinary communication besides the end products might be useful.

8. Conclusion

While the findings contribute to forming guiding principles to implement multidisciplinary teamwork of science and engineering students, the thorough student experiences are largely context specific. The study serves as one of the few exploratory studies on the effective practices in multidisciplinary teams of science and engineering students in a CBL course concluding with pedagogical cues. Researchers are needed to examine if and how the results differ in wider contexts. We hope that the findings can be applicable to similar settings given the thick descriptions and examples (Guba and Lincoln 1981). We plan to build on our findings by exploring multidisciplinary teamwork with new cohorts of science and engineering students in the mandatory CBL courses. Below are notions supported by our findings that can be worthy of consideration for future course implementations and follow-up studies:

- findings affirm the role of the weekly meetings, work on the project plan, stakeholder pitch, and testing in the lab in making disciplinary differences explicit and facilitating connection of disciplines,
- more frequent meetings with problem owners and stronger interaction with the teachers of both disciplines can improve problem formulation,
- scaffolding during problem identification is a critical factor to support students in recognising their gained disciplinary knowledge and in identifying areas for necessary knowledge,
- forming small multidisciplinary sub-teams seems essential to discuss immediate problems using disciplinary perspectives and to reveal differences in problem-solving approaches,
- a positive team environment allowing for joint work and negotiation is important for all members to be present,
- science students' gaining experience in team meetings and willingness to learn unfamiliar topics, engineering students' efforts to engage science students were critical for active participation of all team members,
- bringing together with science students can be a good method to improve project management practices of engineering students.

The study contributes to the recently emerging studies that investigate multidisciplinary teamwork in CBL (e.g. Jensen, Utriainen, and Steinert 2018). Our results serve as a good basis for understanding how boundary interactions emerge across disciplines in the context of an open-ended challenge. For practical implications, the above list of insights can serve as a guideline for course design. The findings also suggest fostering students' problem-identification skills by selecting the challenge focus as related to all disciplines and by using short multidisciplinary challenge prompts. A potential area for future research can be investigating teamwork in a CBL context with less demanding time constraints and a challenge more closely related to AP content. Because the effective mechanisms for interactions in CBL are unclear, another area for research could be understanding how different interaction frequency and structure with stakeholders and different teacher roles can impact teamwork.

Limitations include the fact that this research included a small number of student teams. The number of ME students in the teams was higher then the number of AP students. Also, with a group of volunteering students registering for this course, we can not make any inferences on teamwork in a mandatory multidisciplinary CBL course. It is our plan to conduct a large-scale study to reveal more insightful findings when the course is mandatory. Also, we expect to see increased number of publications in CBL literature with larger student size and with more diverse programmes.

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