THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Unpacking Interdisciplinary Groupwork in Engineering Education

Theory and Practice

MICHAEL TIMOTHY O'CONNELL

Department of Communication and Learning in Science

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2025

Unpacking Interdisciplinary Groupwork in Engineering Education
Theory and Practice

MICHAEL TIMOTHY O’CONNELL
ISBN 978-91-8103-289-5

Acknowledgements, dedications, and similar personal statements in this thesis, reflect the author’s own views.

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 5747
ISSN 0346-718Xhttps://doi.org/10.63959/chalmers.dt/5747

Department of Communication and Learning in Science
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Cover:
Collaborative Learning (photo by Michael Timothy O’Connell)

Printed by Chalmers Digitaltryck
Gothenburg, Sweden 2025

UNPACKING INTERDISCIPLINARY GROUPWORK IN ENGINEERING EDUCATION

Theory and Practice

MICHAEL TIMOTHY O'CONNELL
Department of Communication and Learning in Science
Chalmers University of Technology

Abstract

As more universities introduce interdisciplinary project-based courses into engineering programmes, it is critical to explore their effects on students. These courses typically require groups of students from different disciplines to work together to solve a complex problem that requires the input of different disciplinary knowledge and methods. There is an expectation that working on these projects will result in quality learning.

This thesis, which is based on four papers, sets out to unpack (1) the meaning of interdisciplinary engineering education and (2) the various elements affecting the learning processes of student groups taking part in interdisciplinary project-based courses. As such, the thesis draws on theory and research related to interdisciplinarity, project-based learning, collaborative learning, and social regulation of learning. To achieve the dual aims of the thesis, data was collected from the teachers of, and participants of interdisciplinary project-based courses and was analysed using a qualitative approach.

The thesis argues that interdisciplinarity is best understood as a *travelling concept* and identifies two main conceptions of interdisciplinarity among engineering educators: *epistemic* interdisciplinarity and *social* interdisciplinarity. It also draws on the concept of "interdisciplinarity plus" to characterize settings where students and professionals are co-learners within a project-based course, exploring epistemic practices and positionings mobilized by these two groups. Furthermore, the thesis expands upon the theories of social regulation of learning and collaborative learning to better account for collaboration over the course of an interdisciplinary project. This includes the impact unfamiliarity of group members, disciplinary differences, and the project topic, can have on a group's ability to engage in effective collaboration and regulation of learning. Relatedly, the thesis introduces the notion of "aggressive" co-regulation where a student tries to regulate others using an external person in a position of power (e.g. a teacher).

Based on the findings, I suggest the concept of "common ground" be incorporated into theories of social regulation of learning in interdisciplinary groups. In educational practice, the idea of common ground can be implemented through scaffolding by teachers. Moreover, future studies are required to explore more effective ways to document and support regulation of learning in interdisciplinary project-based courses.

Keywords: interdisciplinarity, collaborative learning, project-based learning, social regulation of learning, socially shared regulation of learning, co-regulation of learning, interdisciplinary engineering education, engineering education.

LIST OF PUBLICATIONS

This thesis is based on the following papers:

Paper 1 O'Connell, M.T., Feng X., Adawi, T., Sundman, J., Routhe, H.W., Wallin, P., Stöhr, C. (*In Review)*. Interdisciplinarity as a travelling concept: Teachers' conceptions of the nature and role of interdisciplinary engineering education. *Undergoing revisions, to be submitted for second round of review in the Journal of Engineering Education.*

MoC and XF conceived the idea and co-designed the study with support from CS. MoC and XF collected the data (with JS helping for one interview). MoC, XF, and JS performed the data analysis. MoC and TA wrote the first draft with contributions from the other authors. MoC, TA, and CS prepared and submitted the final draft.

Paper 2 O'Connell, M. T., Adawi, T., Wallin, P., Stöhr, C. *(In Review)*. Engineering students and professionals as co-learners: Epistemic practices and positioning. *Undergoing a second round of review for a special issue of the European Journal of Engineering Education.*

MoC conceived the idea and designed the study with support from CS. MoC collected the data and performed the analysis of it with overview from TA and CS. MoC co-wrote the first draft with TA, all four authors edited and prepared the final draft. MoC made the required changes after the first round of reviews and resubmitted the final draft.

Paper 3 O'Connell, M. T., Wallin, P., Negretti, R., Stöhr, C. (2023). Social regulation of learning in interdisciplinary groupwork. *European Journal of Engineering Education,* 49(4), 683–699.

MoC conceived and designed the study with input from CS. MoC and CS contributed to the overall conceptualisation (RQs, aims, problem statement) of the study. The data collection was performed by MoC. Data analysis was performed by MoC with input from RN, CS, and PW. MoC wrote the original draft, all four contributors reviewed the draft. MoC, PW and CS then edited the final draft.

Paper 4 O'Connell, M. T., Adawi, T., Dobsicek Trefna, H., Ström, A., Stöhr, C. (2021). Challenge episodes and coping strategies in undergraduate engineering research. In *Proceedings of the 49th European Society for Engineering Education (SEFI) Conference 2021, Berlin, Germany*

TA, HDT and HS designed the study and collected the data. MoC, TA and CS contributed to the overall conceptualisation (RQs, aims, problem statement). MoC performed the data analysis and wrote the first draft. MoC, TA and CS reviewed and edited the draft to produce the final manuscript.

Other relevant contributions

Sundman, J., Taka, M., Feng, X., O’Connell, M., Stöhr, C., Varis, O., & Guerra, A. (2025). Who Am I? How Sustainability-Oriented Problem-Based Learning Shapes Students’ Personal, Disciplinary, and Professional Identity. In *Rajala, A., Cortez, A., Hofmann, R., Jornet, A., Lotz-Sisitka, H., & Markauskaite, L. (Eds.), Proceedings of the 19th International Conference of the Learning Sciences - ICLS 2025 (pp. 2717-2719). International Society of the Learning Sciences.*

Feng, X., Aarnio, H., O'Connell, M. T., Taka, M., Enelund, M., & Keskinen, M. (2024). Re-imagining engineering education through addressing interdisciplinary course design challenges. In *Proceedings of the 52nd Annual Conference of SEFI, Lausanne, Switzerland.*

O’Connell, M. T., Wallin, P., Negretti, R., Stöhr, C. (2023). Tracking Social Regulation of Learning in Interdisciplinary Groupwork. In *Proceedings of the 9th International Research Symposium on Problem-Based Learning: Transforming Engineering Education Conference 2023, Boston, USA.*

Kjellberg, M., O’Connell, M., Bergman, B., Stöhr, C., Larsson, J. (2023) Teachers’ Reflections on their Experiences Teaching Interdisciplinary Project-Based Courses. In *Proceedings of the 51st European Society for Engineering Education (SEFI) Conference 2023, Dublin, Ireland.*

O’Connell, M. T., Stöhr, C., Wallin, P. (2022). Using Challenge Episodes to Identify Social Regulation in Collaborative Groupwork. In *Proceedings of the 18th International CDIO Conference 2022, Reykjavik, Iceland.*

Acknowledgements

As I take the final steps of my PhD journey, I now take time to reflect and thank those who have helped me through the years.

I would like to begin by thanking my supervisors Christian Stöhr, Tom Adawi and Patric Wallin for all of your help. Christian, I am eternally grateful for all your tireless support, encouragement, advice and guidance for my research, courses, and teaching duties. Especially during the periods when I had a heavy workload and needed help coordinating and balancing everything. Tom, I would like to thank you for your support and encouragement in my writing. I especially enjoyed our conversations on my work and the field of EER. Patric, I am especially thankful to you for taking on a larger role than you had perhaps signed up for in the early days of my PhD. Your thoughts and insights have helped keep me on track. Finally, I would like to thank all three of you for taking a chance and offering this PhD position to a middle-aged Irishman that had finished his master's almost 10 years earlier and being so patient and supportive as I returned to academic life and writing.

I wish to thank the Tracks initiative for funding my PhD. I would especially like to thank the Tracks coordinators Mikael and Kristina for their help and support throughout the years with all things Tracks related. I would also like to thank the various Tracks teachers that facilitated me when I was looking for participants for my studies. Next, I would like to thank my colleagues at EER for all their help on both a personal and professional level as I adjusted to living and working in Sweden. I especially wish to thank Malin for her help and advice over the years, particularly in the early years of my PhD as I had to negotiate the move to Sweden during a pandemic. I would also like to thank my fellow PhD students and post-docs at CLS, past and present, for all your support and the fun times we have had over the years. Navigating my PhD journey has been easier with all of your insights.

I also wish to express my gratitude to my various co-authors for the papers that make up this thesis. To Raffaella for her insights and advice on regulation of learning. To Xiaoqi, Julia and Henrik and the researchers at Aalto and Aalborg for all your help in organizing and conducting a study across three universities in three countries. The papers were all the better for all of your contributions. I would also like to express my gratitude for friends back in Ireland that gave advice when I was looking and applying for PhD programmes and their encouragement over the years when I was back on visits: Tom (Farrelly) and Philip.

Finally, I want to thank my family. My wife Jia, who has been my rock in terms of love, support, and encouragement. I wish to thank my two daughters, Aisling and Aoife, who I brought all the way over to a new country on the other side of Europe during a worldwide pandemic. The two of you have achieved incredible things, I am proud of you, and you always brighten my days. To my parents, Michael and Elizabeth, my siblings, Brendan, James, and Claire, I thank you for all your love, support, and encouragement throughout the years.

Michael Timothy O'Connell

Göteborg, August 2025

Table of Contents

1. Introduction

"The ideal engineer is a composite. He is not a scientist, he is not a mathematician, he is not a sociologist or a writer, but he may use the knowledge and techniques of any or all of these disciplines in solving engineering problems." - N.W. Dougherty

I have always enjoyed trying to understand how something works and then putting it into application. This drive has served me well during my undergraduate studies, first in my national diploma in Software Development (equivalent to an ordinary bachelor's degree post Bologna), then in my (honour's) bachelor's in Information Technology (a curious programme that was split between electrical, electronical, and computer engineering). I have applied this drive to sport, both competing and coaching, and in my various careers as Software Tester, Instructional Designer and Educational Technologist. Many years ago, when I enrolled on a master's degree in Educational Technology, this drive caused alignment of sorts and something clicked. It hadn't been my first choice of master's, that was Computer Science, but the university decided to end that degree programme and offered me a place on Educational Technology instead. I had expected the course to be technology heavy and to use it to acquire more technical skills. However, the course was more centred around education rather than technology and ignited an unexpected spark. I found the theories on how people learn fascinating and thinking back on my own education I started to question how it could have been done better. This passion of investigating how learning works, coupled with using that knowledge to explore ways to improve higher level education, has been the motivation behind my research and this thesis. As a researcher, I see myself within the quote above: I like to dip into other pedagogy related fields and see what can be applied or taken into engineering education research (EER) to help improve engineering education. This brings me to this thesis and my research. In the very beginning of my PhD journey, I was given a paper by Hadgraft and Kolmos (2020) to read to prepare for the interview for the position. The paper spoke about engineering students taking part in interdisciplinary project-based courses. I found the idea fascinating and was excited to investigate how such courses work and what effect it would have on the students' learning. This thesis is focused on students taking part in interdisciplinary groupwork, but I must begin with a brief description of the educational and theoretical landscape it takes place in.

Recent years have seen universities re-evaluate how they educate engineering students in order to better prepare them for the challenges facing society that engineers are expected to help resolve. Engineers of today are expected to ensure their solutions to problems are compatible with sustainability goals and be aware of the impact their work has on society (Hadgraft & Kolmos, 2020). The complexity of the aforementioned challenges requires engineers to work with others from different disciplines and backgrounds to form complete solutions. However, working in such groups can be challenging in itself as members can have vastly different perspectives, experiences, work procedures, content knowledge, and even different meanings for the same words (Buanes & Jentoft, 2009). This can be potentially jarring for newly graduated engineers, who might have only ever worked with classmates on projects within their own discipline. The call for engineering education to prepare students for this industrial landscape has not been limited to institutions of higher education. Both students and recent graduates have highlighted the need for better preparation for future work environments (Kolmos et al., 2018; Wallin et al., 2017).

One-way universities have responded to this challenge is to introduce opportunities for students to work in groups with others from different disciplines on complex problems (e.g. Enelund & Briggs, 2020; Crawley, 2018). While the focus is on groupwork, these activities typically take place in project-based courses, making use of the concept of project-based learning (PjBL), though some are in the form of undergraduate research experiences (UREs) which share many similar features with PjBL. In these courses student groups are presented with open-ended or ill-structured problems and are required to create their own project goal and plan. The projects and solutions the students create require knowledge of more than one discipline and will therefore need to be interdisciplinary in nature.

One example of a programme offering interdisciplinary project-based courses is Chalmers University of Technology's (hereafter Chalmers) Tracks initiative, which was launched in 2019. Tracks offers students the opportunity to take part in project-based courses which are built upon "real world" problems or are related to current research and are offered as electives that sit outside of standard curricula (Enelund & Briggs, 2020). The courses therefore offer students the opportunity to work in groups with others from different disciplines on interdisciplinary projects. Tracks is designed to be flexible in its organization, allowing courses to be designed and implemented far quicker than those within traditional curricula (Enelund & Briggs, 2020). Courses are generally open to all students, but sometimes limiting criteria are applied, where applicants need to have certain disciplinary knowledge or be an "advanced" student (i.e. studying at master's level or higher). In addition to bachelor's and master's students, the courses are also open to PhD students, and sometimes to alumni or professionals from outside the university. This thesis relies intensively (but not exclusively) on Tracks courses as an empirical base.

Although initiatives such as Tracks are touted as a solution to the challenge of preparing engineering students for their future careers, the implementation of interdisciplinary courses within engineering education raises some questions which this thesis seeks to address. The first and most basic being: What do we mean when we use the term interdisciplinarity? While the term interdisciplinarity has widespread use, it is understood differently across different fields of study (e.g. Klein, 2010a), and even scholars within the same field can disagree on its definition (e.g. Repko, 2007). **Paper 1** puts forward the argument that the field of EER has tended to borrow definitions of the term from other fields without theorizing what it means within engineering education. It addresses this by examining how engineering teachers across three universities in the Nordic area conceptualise interdisciplinarity. Engineering teachers were chosen as it is important for their views and conceptualizations to be considered when we as researchers theorize key concepts related to education, such as interdisciplinarity (Lattuca, 2003). This paper places teachers' perceptions of the nature and role of interdisciplinarity in a theoretical context.

With the expansion of interdisciplinary project-based courses comes opportunities for the participation of non-academic actors. Such scenarios, where non-academic actors are enrolled on a course and take part in project work with students, fall in-between interdisciplinarity and transdisciplinarity, requiring a rethinking of or expansion of the interdisciplinary paradigm. **Paper 2** utilises Repko and Szostak's (2017) concept of "interdisciplinarity plus" to describe this theoretical space between the two and to frame a study of students and professionals that were enrolled together on an interdisciplinary project-based course. The paper investigated the epistemic practices of groups comprised of students only, professionals only, and mixed groups. Additionally, it examined how students and professionals positioned themselves, each other, and the project they worked on.

As mentioned, interdisciplinarity is only one element of the change implemented by universities, with the other being groups collaborating on projects or problems. This raises the question of how engineering students adapt to working in groups with individuals from other disciplines and on potentially unfamiliar topics. **Paper 4** examines the experiences of engineering students working together as part of UREs, including the challenges they faced and the coping strategies they implemented in response to them.

There is an expectation that student groups working together on projects will naturally engage in collaborative learning (Summers & Volet, 2010; De Hei et al., 2015). Collaborative learning occurs when groups actively learn together, and this is desirable as there are many social, psychological and academic benefits from engaging in collaborative learning (Laal & Ghodsi, 2012). However, simply having students take part in groupwork will not guarantee they will engage in collaborative learning (Summers & Volet, 2010), so we must look for ways to initiate and support it. As a concept, collaborative learning is quite broad with numerous different theories and ways to conceptualize it (O'Donnell & Hmelo-Silver, 2013; Stahl, 2013). This thesis takes the approach that it can be broken down into smaller processes which can be studied. For collaborative learning to occur students must engage in two processes: content processing (the acquirement and co-construction of knowledge), and the regulation of said content processing, which is better known as "social regulation of learning" (SoRL) (Summers & Volet, 2010; Järvelä & Hadwin, 2013).

While SoRL as a concept has been developed over the last twenty years, there remains a dearth of studies that examine how it is enacted by a group over the course of a project. Studies on the topic also typically attempt to identify SoRL within monodisciplinary groups and not interdisciplinary ones (e.g. Malmberg et al., 2015). This is probably due to a combination of the general lack of interdisciplinary project-based courses until the recent increased interest in them and the relatively new concept of SoRL. **Paper 3** addresses this gap in the literature by examining how interdisciplinary student groups engage in SoRL and collaborative learning over the course of a project.

To summarize, the aim of this thesis is to "unpack" (1) the meaning of interdisciplinary engineering education and (2) the various elements affecting the learning processes of student groups taking part in interdisciplinary project-based courses. To do this I will examine each of the different aspects of interdisciplinary project-based group work and look to see how they relate or affect each other. I must point out that my goal is not to measure learning, or to determine whether a group has achieved interdisciplinarity, or engaged in successful collaborative learning. Rather, I am looking to explore how groups operate in this environment what processes and practices they engage in.

1.1 Thesis outline

This thesis is structured in the following way. Chapter 2 establishes the position of this thesis in terms of previous research and outlines its theoretical framework. It begins by introducing the thesis' fundamental concepts and stating where it lies in relation to them. It also provides a brief overview of the theoretical landscape this thesis is situated in. In Chapter 3, I begin with an outline of my epistemological and ontological position. As readers might be unfamiliar with the Swedish education system and Tracks, I will provide a brief description of the context and settings in which the papers took place. This is followed by a discussion of the data collection and analysis methods used for all four papers. Here I will not only explain the "how" but also the "why" behind the methodologies used for the papers. Next, Chapter 4 will provide a summary of each of the four papers. This is followed by Chapter 5, where I will discuss the findings of the papers and their contributions to theory and practice. Finally, I will provide a conclusion to the thesis in Chapter 6. The four papers are appended after the bibliography.

2. Conceptual and Theoretical Framework

This thesis draws on different concepts, such as interdisciplinarity, collaborative learning, the regulation of learning, and project-based learning. It is guided by the learning paradigms of social constructivism and sociocultural theory. I will use this chapter to provide an outline for my theoretical framework. However, I must point out that my intention is not to write an in-depth or comprehensive description of each element, but to provide the reader with enough insight to better understand this thesis and the four papers it is built on.

2.1 Interdisciplinarity

Interdisciplinarity is a core concept of this thesis and is a component in all four of its research papers. Within the field of engineering education, interdisciplinarity is recognised as an essential skill for future engineers (Hadgraft & Kolmos, 2020) and is a key element of university initiatives seeking to better prepare engineering students for their future careers (e.g. Enelund & Briggs, 2020). The concept is gaining popularity, with studies exploring numerous aspects of interdisciplinarity in engineering education. These studies often focus on the skills students can achieve from interdisciplinary education (e.g. Lattuca et al., 2017), on how interdisciplinary courses can or should be developed (e.g. Klaassen, 2018), or where interdisciplinarity is part of the environment the study is examining (Wallin, 2020). Other studies examine engineering teachers' ability to differentiate between different key concepts such as multidisciplinarity, interdisciplinarity, and transdisciplinarity (e.g. Feng et al., 2023; Lattuca et al., 2013). With the increasing use of interdisciplinarity in both curriculum development and educational research, one might be forgiven for believing that there is one overarching definition or understanding of what it actually is. While it is true that other fields of study might have spent far more time theorizing interdisciplinarity, it would be a mistake to believe that they are unified in their conceptualizations of it. Due to its importance to this thesis, I will therefore begin by exploring what interdisciplinarity is.

2.1.1 What is interdisciplinarity?

In the beginning of my doctorial journey, I defined interdisciplinarity in very simple terms: interdisciplinarity occurs when knowledge from two or more disciplines are integrated to form a more comprehensive understanding (Newell, 2001). Unfortunately, while succinct, this definition does not provide a good account of the nature of interdisciplinarity. Furthermore, by borrowing a definition from Newell without exploring deeper into the concept of interdisciplinarity I unknowingly aligned myself with one of the concept's theoretical fault lines. So, if we are to better understand the effects of interdisciplinarity on learning (how or what students learn), then I need to first delve into its nature and what we mean when we talk about "interdisciplinary education".

I will begin with the division between what is known as the "generalists" and "integrationists", which is centred around the notion of *integration* and whether or not it has a role in interdisciplinarity. Generalists see any interaction between disciplines to be interdisciplinary, sometimes with minimal contact (Repko, 2007). For some of those that subscribe to the generalist perspective, integration is perceived to imply a power imbalance between disciplines (Lattuca, 2003). Conversely, integrationists see integration as a requirement for interdisciplinarity. From an integrationist perspective, the bringing together of disciplines without integration is considered to be multidisciplinarity (Klein, 2010b). Integration is, however, not guaranteed, and within a group context it requires the development of common ground and language (Repko, 2007). By forming a common ground, the group members will be able to relate and rationalise the different perspectives and knowledge from their individual disciplines (Newell, 2001). The use of phrases such as “common ground”, “common language”, and even what Repko (2007) refers to as “collaborative language”, points to the need for collaboration. This brings me to the next debate on interdisciplinarity: the role of collaboration.

Interdisciplinarity, especially within engineering education, is often equated with collaboration. According to Boden (1999), there are different types, or levels, of interdisciplinarity that depend on the degree of collaboration and cooperation between people from various disciplines. For Boden (1999), groups can achieve some level of interdisciplinarity even with minimal collaboration and integration, though they need more of both to attain higher levels of interdisciplinarity. Fiore (2008) equates interdisciplinarity with teamwork but argues this is because the bank of disciplinary knowledge has become too large for an individual to develop a deep understanding of a single discipline. The belief that collaboration is essential is most likely due to the form that interdisciplinarity often takes in higher level education – that of groups working on a complex problem with members coming from different disciplines. Of course, as Klein (2010b) points out, despite a sizable belief in the contrary, collaboration is not necessary for interdisciplinarity. This is an important point as the insistence on collaboration negates several opportunities for individuals to engage in any form of interdisciplinarity. This might seem like a moot point in a thesis that examines groups engaged in project work, but I believe it is an important point to make as it applies to monodisciplinary groups too. The collaboration the theorists above refer to is that between disciplines, which could be construed as excluding monodisciplinary groups.

As I mentioned above, I suspect that collaboration is closely associated with interdisciplinarity as interdisciplinarity is often introduced through group project work (e.g. Frank & Barzilai, 2004; Hsu & Liu, 2005; Ríos et al., 2010). This leads me to another point of contention among interdisciplinarians that is framed in terms of “instrumental” versus “critical” interdisciplinarity. Instrumental interdisciplinarity is centred around, or focused on, using different disciplines in solving complex problems (Klein, 2010a; Stoller, 2020). Critical interdisciplinarity, on the other hand, “interrogates the dominant structures of knowledge and education with the aim of transforming them” (Klein, 2010a, p.23). Stoller (2020) argues that, while some adherents of critical interdisciplinarity see it as dismantling disciplines, it does not necessarily need to be so. Instead, Stoller (2020) suggests that critical interdisciplinarity can take the form of a “critical democratic dialogue”, where disciplines are part of a dialog that which aims to further understanding. Despite their differences, it has been argued that instrumental and critical interdisciplinarity are not necessarily incompatible with each other as Welch (2011) argues that combining them provides a more holistic approach to interdisciplinarity. Similarly, Martins et al. (2023) proposes a framework for higher level education that combines both. According to Martins et al. (2023), the critical interdisciplinarity aspects allows the students to connect a problem and solution with society and sustainability, while instrumental interdisciplinarity allows for an application of what students learnt in their curriculum with a focus on career development.

There can be a temptation to instinctively assign a theoretical position on interdisciplinarity to disciplines or fields of study. This is understandable as disciplines themselves incorporate not only knowledge and perspectives, but also contain their own cultures, vocabulary, epistemological positions (Buanes & Jentoft, 2009), and sometimes even their own pedagogies (English, 2016). Added to this, is how theorists often discuss interdisciplinarity in relation to fields of study (e.g. Newell, 2001; Klein, 2010b). However, we should be careful not to automatically assign a theoretical position based on discipline. This is highlighted in a study by Lattuca (2003), who notes that while there is some alignment between faculty members' disciplines and whether or not they were a generalist or integrationist caution is warranted as this alignment is not guaranteed. Additionally, Ming et al. (2024) found there was no consensus among engineering educators on how to define interdisciplinarity, which suggests they are utilizing different definitions from other fields. We therefore need to be careful not to assume a borrowed definition of interdisciplinarity is universal as there can be disputes on it even within the same discipline.

Having outlined, briefly, some of the competing theories on interdisciplinarity, the question is: What is my position and the position this thesis takes? Due to the phenomena it studies and the setting in which it takes place (interdisciplinary project-based courses) this study aligns with instrumental interdisciplinarity. While I acknowledge that collaboration is not required for all instances of interdisciplinarity, I consider it to have a significant role with groups in this setting. Finally, I still consider integration to be an integral element of interdisciplinarity and therefore take an integrationist position. However, this position presents a potential predicament. From an integrationist perspective it is possible for a group of students from different disciplines to work on a project together and to only achieve multidisciplinarity. This thesis, and the research it is based on, does not set out to determine the level of interdisciplinarity groups achieve (if at all). Rather, my work aims to examine the impact interdisciplinarity has on a group's learning processes. I reconcile this quandary in two ways. First, I refer to the aforementioned work of Boden (1999) that outlines how even with minimal integration and collaboration it is possible to attain a (minimal) level of interdisciplinarity. Second, interdisciplinarity is not limited to groups. In environments such as Tracks, interdisciplinarity is embedded within the course designs, the course literature, and the problems and project topics presented to groups. Additionally, the solutions produced by groups are required to be interdisciplinary. I believe this allows me to study the effects of interdisciplinarity without having to prove whether (or how much) a particular group has achieved it.

I will conclude with one final note that is relevant to the setting in which most of the papers in this thesis is set. As the groups within three of the papers were primarily STEM students or graduates, the groups could be labelled as "narrow" interdisciplinary since the participants' disciplines share similar epistemologies, methods, knowledge, or beliefs (Kolmos et al., 2024). While this can be a legitimate designation, I feel it often leads to an assumption that STEM disciplines are closer than they often really are. It should not be assumed that someone with a degree in mechanical engineering will automatically understand and be able to work with someone from computer science, architecture, or biology.

2.1.2 Interdisciplinarity and Learning

While the previous section outlines the different theoretical perspectives on what interdisciplinarity is, there are also conceptions on how it works in regard to learning. An example is the perception that disciplines are distinct entities whose knowledge can be taken and combined (Bernini & Woods, 2014) or that disciplines are akin to institutions (Buanes & Jentoft, 2009). One such conception that I will include in this thesis is that of cognitive integration, which Bernini and Woods (2014) propose as a model for interdisciplinarity. Cognitive integration considers that cognition extends beyond the individual mind as one can use cognitive processes on "external vehicles" (Menary, 2010, p281). Menary (2010) gives examples such as our use of language to shape our environment or using a pen and paper to solve mathematical problems. Bernini and Woods propose cognitive integration as a way to include individual's cognition in interdisciplinarity rather than simply seeing it as "a disembodied interaction of disciplines" (Bernini & Woods, 2014 p.605). While they discuss cognitive integration in relation to interdisciplinary research, I include it in this thesis as I can see its relevance to individuals in a group and the processes they engage in to achieve interdisciplinarity and collaborative learning. However, there is another perspective of interdisciplinarity I wish to bring attention to and incorporate into this thesis: the sociocultural perspective. From a sociocultural perspective the examples of language or pen and paper can be considered cultural tools and form part of an analytical framework.

Sociocultural theory acknowledges the importance of social interactions on learning, while also taking into consideration how learning is affected by culture and environment (Ameri, 2020). It is learner centred and considers learning to be ingrained in social and cultural contexts (Wang, 2011). In terms of authentic learning, giving projects a sociocultural context helps students to relate their learning to the real world and makes it something tangible or practical (Adams, 2006). My use of the paradigm might seem at odds with my (and the participants in my papers) instrumentalist perspective of interdisciplinarity. This is addressed by McMurtry's (2011) observation that interdisciplinarity is predominantly perceived through either phenomena or a sociocultural perspective, with both perspectives considering themselves to be the true representation of interdisciplinarity. However, McMurtry asserts that rather than being rival perspectives they should be viewed as complimentary to one another.

Sociocultural theory is relevant for this thesis as interdisciplinary groups will inherently have members view tasks through different contexts with disciplines that have their own cultures. In this case my use of culture "includes the collection of customs, attitudes, values, and beliefs that characterizes one group of people and distinguishes them from other groups" (Flynn, 2023 p.1). Initiatives such as Tracks also have many students from diverse cultural and societal backgrounds enrolled on the courses. From a socio-cultural perspective an interdisciplinary group working on a project should lead to them forming a community of learners with themselves as members working to achieve a common goal (Wang, 2011).

So far in this background section my focus has been on what interdisciplinarity is and how it relates to one of this thesis' learning paradigms, but why should we introduce interdisciplinarity to engineering education? How do students benefit from it? It is important to first look at what we should not expect from students engaging in interdisciplinary groupwork. Interdisciplinary groupwork on a project can provide an opportunity for students to gain both disciplinary specific knowledge as well as non-disciplinary skills (Bogdanovs et al., 2022). However, students are not expected (or should not be expected) to become experts in a variety of disciplines. Instead, the more valuable outcome from interdisciplinary education is the development of higher order thinking skills and new epistemological perspectives (Ivanitskaya et al., 2002). In the case of PjBL – where there is focus on solving a problem or achieving a goal – the act of integrating knowledge from different disciplines will result in the creation of a new perspective on it (Stentoft, 2017). It is perhaps unsurprising then that the outcomes for interdisciplinary education are typically expected to be related to skills such as problem solving, analytical thinking, communication, teamwork, and project management (e.g. Rhee et al., 2020).

2.2 Project-based Learning

While Interdisciplinarity can be applied to a broad range of contexts my research is centred on interdisciplinarity in terms of project work in education. It is important then that I provide some insight into PjBL: what it is, why it is used, and its relevance to this thesis.

Working on authentic or real-world challenges allows student groups to apply their academic knowledge and engage in collaboration in order to solve them (Brundiers et al., 2010). The prospect of working on such problems can lead to an increase in engagement and motivation (Guardiola et al., 2013). It can also introduce students to challenges that engineers encounter in the "real-world", such as scope creep, taking stakeholders or end users into account, and dealing with ambiguity, among other things (Guardiola et al., 2013). Therefore, PjBL is one way that universities can incorporate working on authentic problems into their programmes (Brundiers et al., 2010). Within PjBL, students are expected to take control of all aspects of a project, including the planning, designing, implementation, and evaluation of their work (Frank & Barzilai, 2004; Ríos et al., 2010). Strictly speaking, the projects can be worked on by individuals or groups, but this thesis is only concerned with the latter.

Participation in PjBL tends to result in deeper learning (Garcia & Garcias, 2012) and can promote critical thinking skills (Issa & Khataibeh, 2021). Taking part in PjBL can provide students with a deeper comprehension of subject matter and processes, as well as competencies and skills that can later be applied to "real" problems in industry (Frank & Barzilai, 2004). This includes improvements in students' communication and discourse skills, self-esteem, and how to make decisions as a group (Frank & Barzilai, 2004). This is an important aspect of PjBL as professional competencies will prepare students for their future careers and will require students to become aware of and develop their own competencies leading them to create their own learning trajectory (Hadgraft & Kolmos, 2020). There is considerable overlap then with the competencies that are expected to be gained from interdisciplinary education, which I mentioned in the previous section on interdisciplinarity. While skills such as problem solving, communication etc are not exclusive to PjBL or interdisciplinarity, their combination in interdisciplinary projects should lead to the stronger development of such skills.

PjBL can be used to introduce students to complicated and complex problems, which often leads to interdisciplinarity as such problems cannot be adequately solved within one discipline (Hadgraft & Kolmos, 2020), though it should be noted that not all PjBL is interdisciplinary. From an interdisciplinary perspective, having students focus on a problem will encourage them to effectively create links between strands of disciplinary knowledge which they would otherwise not have made (Ivanitskaya et al., 2002). In terms of groupwork, broad and complex tasks can lead to better collaborative learning as they require groups to engage in discussions and rely on all members' contributions (Scager et al., 2016). However, as PjBL requires students to plan their projects, such complex problems can result in uncertainty and frustration in the beginning, especially for students who are novices to these activities (Frank & Barzilai, 2004). Student's previous knowledge and experience with project work is therefore important in these early phases (Hsu & Liu, 2005). To help groups navigate this uncertainty, teachers can provide scaffolding in the form of questions, technology, learning environments, coaching (Singer et al., 2000), and weekly meetings (Frank & Barzilai, 2004).

Not all project work is, strictly speaking, PjBL. One of the papers that make up this thesis is based on UREs, which share many commonalities with PjBL, but also some notable differences and therefore need their own introduction. UREs aim to engage students in real research in an authentic STEM environment. There are a number of different forms UREs can take, such as internships with industry, where one student works with professionals, or course-based UREs, which are embedded into the curriculum (Kumbhar et al., 2018; Gentile et al., 2017). While it is important to note that not all UREs are project-based, the UREs for **Paper 4** took the form of projects with student groups working over the summer period for which they received a wage. However, while learning was an important outcome, they were not courses with clearly defined learning outcomes, credits, or classes.

Taking part in UREs can help students to develop an identity as a researcher as well as the relevant skills needed for such a role (Olivares-Donoso & González, 2019; Lopatto, 2004; Wallin et al., 2020). These skills include data collection and analysis, being able to effectively communicate one's work, performing tasks in the laboratory, communicating effectively with teammates, understanding the research process, and gaining a researcher's thought processes (Lopatto, 2004; Wallin et al., 2020). It is important that participants actually engage in proper research work and not simply following a list of directions like a recipe (Kumbhar et al., 2018). This can be difficult on the students as they might expect the work to be similar to their usual laboratory classes or projects that will have clear guidance and predictable outcomes (Cartrette & Melroe-Lehrman, 2012). This is why UREs should expect the students to form their own research questions and project plans within the laboratory's overall project (Wallin et al., 2020).

UREs are generally seen as valuable learning experiences by students as they can gain the ability to work independently in a laboratory and become more resilient when faced with challenges (Lopatto, 2010; Wallin et al., 2020). However, there is another dimension to UREs and that is to promote research at post-graduate levels and careers in the area. Taking part in UREs usually cements students' intentions to pursue further education, and career paths, in research (Lopatto, 2004). UREs can also make previously disinterested students consider a research career. Alternatively, previously interested students may decide that such a career is not for them.

At this point I will introduce the second learning paradigm of this thesis: social constructivism. PjBL is built upon social constructivism, which states that that knowledge is constructed through interactions or collaboration with others (Singer et al., 2000); it differs from cognitive constructivism which sees knowledge as being constructed within individuals (Kalina & Powell, 2009). Social constructivism sees learning as a social process, influenced by society and groups, where learners actively construct meaning and knowledge together (Adams, 2006). By taking part in PjBL students will construct and give meaning to new knowledge that they gain over the project (Issa & Khataibeh, 2021), while also drawing on and applying previous knowledge, including individual disciplinary knowledge (Hsu & Liu, 2005). The process of knowledge creation takes place when the interactions and the knowledge created by them adds to existing knowledge to create new knowledge (Ríos et al., 2010). This process of knowledge creation, described by proponents of PjBL, therefore aligns with social constructivism (Kalina & Powell, 2009). Social constructivism is equally relevant to interdisciplinary education. Stentoft (2017) argues that interdisciplinarity involves the constructing of knowledge from various disciplines and is therefore rooted in constructivism.

My use of both socio-cultural theory and social constructivism will allow for a more thorough examination of student group's learning. Rather than viewing both as competing paradigms, Cobb (1994) asserts that they are complimentary or two sides of the same coin. I therefore take a similar position to Packer and Goicoechea (2000), in that social constructivism explains how knowledge is constructed through interactions, and sociocultural theory places that learning within a cultural context, which the group forms and manages. Thus, both paradigms contribute to an understanding of learning during group work.

The concepts of interdisciplinarity and PjBL are important to this thesis as they feature heavily in both it and the papers it is built on. However, these concepts alone cannot provide sufficient insight into how groups work and learn together. For that we need to consider theory related to collaborative learning.

2.3 Collaborative Learning

As I mentioned in the introduction, having students from different disciplines work together on projects is central to initiatives that universities are implementing to improve engineering education. This thesis aims to investigate what happens within these groups, how they learn and what effect does this set up have on their learning. To do this, I have chosen collaborative learning to be a core concept of this thesis and my research. However, the concept is quite broad, and it is difficult to provide an absolute and concise definition of collaborative learning. Dillenbourg attempted to provide an all-encompassing definition of collaborative learning as "a situation in which two or more people learn or attempt to learn something together" (Dillenbourg, 1999 pg1). Though, as Dillenbourg admits, this broad description can be a little unsatisfactory and this milquetoast definition does little to help explain how it works.

There is an expectation in universities that student groups working together on projects will naturally engage in collaborative learning, but this is a fallacy (De Hei et al., 2015; Summers & Volet, 2010). For one, there is a difference between a group engaging in collaborative learning and simply focusing on completing a task or project (Volet et al., 2009). Collaborative learning occurs when groups actively learn together, and is desirable as there are many social, psychological and academic benefits from engaging in it (Laal & Ghodsi, 2012). However, simply having students take part in groupwork will not guarantee they will engage in collaborative learning (Summers & Volet, 2010), so we must look for ways to identify it, initiate it, and support it. As I mentioned previously, the concept of collaborative learning is quite broad with numerous theories and ways to conceptualize it (O'Donnell & Hmelo-Silver, 2013; Stahl, 2013). However, I must choose one and therefore align with the theory that for collaborative learning to occur students must engage in two processes: content processing (the acquirement and co-construction of knowledge), and the regulation of said content processing, which is better known as *social regulation of learning* (SoRL) (Summers & Volet, 2010; Järvelä & Hadwin, 2013).

2.3.1 Co-construction of Knowledge

Groups engage in the co-construction of knowledge first by sharing knowledge and establishing a common ground within the group, then by building upon said common ground by adding new information or making connections between existing strands of information (Beers et al., 2005). However, while essential, coming to a shared understanding of a problem or solution can be challenging when groups are made up of individuals from different disciplines, each with their own epistemic practices and beliefs (Arthars et al., 2024). This process is not automatic: it requires the sharing of knowledge and perspectives, and negotiation within the group (Beers et al., 2005). An important activity in the co-construction of knowledge is a group coming together and summarizing or discussing what they know (Barana et al., 2023; Vuopala et al., 2019). This enables them to identify dissonance and helps to ensure everyone shares the same understanding, leading to them encoding the new knowledge. This process typically will involve negotiation, especially in interdisciplinary groups or groups working on interdisciplinary problems (e.g. Beers et al., 2005).

High level knowledge co-construction requires groups to actively engage in collaboration and joint learning activities; how much an individual in the group will benefit depends on their commitment (Vuopala et al., 2019). Interestingly, according to Barana et al. (2023), the level of commitment on a group level to such engagement through discussions, knowledge sharing, choosing solutions and corroborating information is more important than individual group member's grades. Barana and colleagues found that homogenous groups with academically low achievers (in terms of their average grades) engaged in better knowledge co-construction than groups of high achievers because they were more enthusiastically and actively engaged in collaboration. A key point is the focus of a group's enthusiasm towards collaborative activities (Barana et al, 2023) as opposed to groups that are highly motivated but focus more on content and completing tasks than engaging in collaborative learning activities (Volet et al., 2009). Something of note in Barana et al.'s (2023) study was their observation that the low achieving groups did not have anyone take on the role of an expert or leader, which they believe led to a more inclusive environment where everyone felt they could contribute. This seems at odds with interdisciplinary groups, where individuals can become their group's expert in tasks related to their discipline, yet still maintain an inclusive environment.

Summers and Volet (2010) point out how a group that works individually on tasks (as opposed to working together on tasks) and then puts their work together at the end is not engaging in knowledge co-construction or collaborative learning. In such a scenario, the groups are focused only on managing their work and producing an end product, rather than collaborative learning (Summers & Volet 2010). However, I believe this could be misinterpreted and as a result might result in the belief that a group sharing out tasks automatically disqualifies them from collaborative learning. While working together on tasks can lead to a high level of co-construction of knowledge and collaborative learning, I believe groups can still engage in both if they share out tasks. The key is the processes and activities they engage in throughout their project. This can be particularly relevant to interdisciplinary groups where, as previously mentioned, individuals are not expected to become experts in other disciplines, so it would make sense for them to assign tasks based on expertise for efficiency and time management.

With these differences in how groups construct knowledge in mind, I believe there are different levels of collaborative learning a group can achieve. Volet et al. (2009) created a framework that allows us to determine the quality of learning a group can achieve based on how they worked. The framework has two axis: one that represents knowledge (from acquiring knowledge to constructing meaning) and one that represents regulation (from self-regulation in a group to co-regulation). This was further adapted by Summers and Volet (2010) to differentiate between high- and low-level regulation (self- and co-) and content processing. However, I feel the adapted version is still lacking as it only considers a group to be engaging in high-level regulation if they are also engaging in high-level content processing.

Using Summer and Volet's framework as a base, I have created an adapted version – see Figure 1 – that represents the various ways that groups can work in relation to both social regulation and the construction of knowledge. It demonstrates how groups can engage in a high level of one component of collaborative learning but a low level of the other, resulting in poorer learning. The optimal situation for learning to occur is for a group to co-construct knowledge and meaning together and engage in high-level social regulation.

		Regulation of Learning	
Construction of Knowledge		**Low-quality**	**High-quality**
	High-Quality	Group works together to try and co-construct knowledge, but engages in low-quality regulation	Group engages in high-quality regulation and works together to co-construct knowledge
	Low-Quality	Group engages in low-quality regulation and constructs knowledge as individuals	Group engages in high-quality regulation, but constructs knowledge as individuals

Figure 1: A framework that outlines the different ways a group can regulate their learning and construct knowledge.

2.3.2 Social Regulation of Learning

SoRL is the other component of collaborative learning within the theoretical framework of this thesis. SoRL was developed out of an expansion of self-regulated learning (SRL) to better represent how the regulation of learning occurs within groups. There are competing theories on what modes of regulation SoRL is comprised of, with some theorists using similar names to describe different actions (e.g. co-regulation). For this thesis, and my research, I align with the theory of there being three modes of regulation: *self-regulation of learning* (SRL), *co-regulation of learning* (CoRL), and *socially shared regulation of learning* (SSRL). I will outline all three modes of SoRL according to the theorists and models that best align with my own position.

I will begin with SRL which has been described as the cornerstone of SoRL by Hadwin et al. (2017). There are different models of SRL, and various theorists often use definitions that can differ from one another. Within models of SRL, learners are not passive in their learning: they construct goals, strategies, and their own meaning from both external and internal sources (Pintrich 2000, 2004). From the literature a broad definition of SRL is: the ability to take control of one's learning through processes related to metacognition, cognition, behaviour, emotion, motivation, and to some extent one's environment, through iterations of activities such as planning, monitoring, evaluation, and change (Hadwin et al., 2017; Pintrich, 2004; Zimmerman, 2015). There are several different models of SRL which have various numbers of phases (e.g. Printrich 2000; Winne & Hadwin 2008). However, despite the differences in the names and number of phases, they cover similar processes and stages of regulation. For this thesis, and my work, I have chosen to use Zimmerman's model of SRL (Zimmerman 2000). I chose this model over others as it appears more streamlined with three phases: forethought, performance, and self-reflection. The forethought phase is when the student analyses the task they are about to do, sets themselves a goal, and creates a plan to achieve it. This phase also considers their motivation and interest in the task their expectations or standards. The performance phase is where the student enacts their plan and works on the task. In this phase they will employ strategies and processes, while also monitoring their work to ensure it is up to standards set in the forethought phase and will be completed on time. In the self-reflection phase, the student evaluates whether the goals were achieved, and their standards met. If the standards were not met, they will determine why this was so. They will also engage in self-reflection on their work and learning, which will affect the forethought phase of their next cycle, such as whether they need to raise their standards. While the model is presented as an iterative cycle, with each phase contributing to the next, students can jump to different phases if needed. An example would be if during the performance phase the student realises the plan is missing something they can jump back to the forethought phase to rework the plan. To expand this model for groups and SoRL, we simply need to adapt it to reflect the roles that group members take during regulation: who is doing the regulating and who is being regulated?

While there is a divide in the literature on what constitutes CoRL, I take the same position as theorists such as Hadwin and Järvelä. For them, CoRL is when individuals' regulation activities are "guided, supported, shaped, or constrained by and with others" (Järvelä & Hadwin, 2013, p28). I often refer to this definition for two reasons: it shows how the person(s) doing the regulating can be a help or a hinderance, and it shows how CoRL is not always a "one-on-one" process. The role of the regulator is not static, but can fluctuate among group members, with individuals taking on roles of capable other and novice as needed (Hadwin & Oshige, 2011). Though as I mentioned, it is not always one–on-one and one person can take the role of capable other for the rest of the group, or the group can come together to regulate one member (and various combinations in between). There are even occasions when the regulation is external, which typically occurs when a teacher or tutor regulates a student or group of students (Hadwin & Oshige, 2011). Ideally, for effective CoRL, group members need to be aware of other members' personal goals, progress, and contributions, and need to monitor them, stepping in when they need help (Miller & Hadwin, 2015). Apart from a member asking for help, co-regulation is often trigged when a group member expresses a misconception or when it becomes obvious to the others that said member lacks understanding of a concept or subject (Ucan & Webb, 2015). How groups or individuals co-regulate each other can have a profound impact on the effectiveness of said regulation. The regulation can be facilitative where the regulator is encouraging and inclusive, or directive where the regulator is controlling and uses negative language (Rogat & Adams-Wiggins, 2015). The former should be encouraged as a positive socio-emotional environment not only allows group members to feel comfortable monitoring each other to seek or give help (Ucan & Webb, 2015), but also because such an environment is crucial for a group to attain SSRL (Rogat & Adams-Wiggins, 2015).

SSRL is the joint regulation of a group by the group itself, meaning that the group shares the regulation (Vauras et al., 2003). This joint regulation requires consensus and sometimes negotiation as groups create joint goals, standards and plans (Hadwin et al., 2017). They will then use these to monitor and evaluate the work, the group, and the group's learning. For a group to engage in SSRL effectively, they will all need to be aware of the joint goals to have the same perspective of what is expected of them and know the group's strengths and weaknesses (Miller & Hadwin, 2015). It can be considered a transactive process as it emerges over time through group interactions and exchanges (Hadwin et al., 2017). While activities such as goal setting, planning, monitoring, and evaluation should naturally require a group to engage in SSRL, there are other triggers. Examples include when a group member voices doubt about a strategy or task, when members begin to express conflicting ideas, or when the group considers whether there needs to be a change in their joint strategy plan or goal plan (Seiradakis & Spantidakis 2019; Ucan & Webb 2015). The tasks or the project the group works on can also have an impact on their SSRL. Tasks perceived to be more complex or difficult will result in more SSRL than those perceived to be easy or straightforward. Similarly, ill-defined questions and multidimensional tasks also spur or initiate SSRL (Iiskala et al., 2011; Iiskala et al., 2015).

To reiterate, the difference between all three forms of regulation – self-regulation, co-regulation, and shared regulation – is determined by the subject and object of the regulation, i.e. who is being regulated by whom. However, these three forms of SoRL are not completely independent of each other: rather, a certain synergy exists between them (see Figure 2). SRL is ingrained in episodes of both SSRL and CoRL (Malmberg et al., 2017), and the better group members are at SRL the better the group itself will be at SSRL (Panadero et al., 2015). Additionally, CoRL can be seen as transitional as it can result in the emergence of SRL or SSRL within a group (Hadwin et al., 2017, Malmberg et al., 2017). Similarly, both CoRL and SSRL can lead to a group member developing a better ability to engage in SRL (DiDonato, 2013). Finally, despite the word "self" being in its name, SRL within a group context does not mean the group member is completely independent as their individual goals and efforts should be in line with and support the group's joint goal (Hadwin et al., 2017).

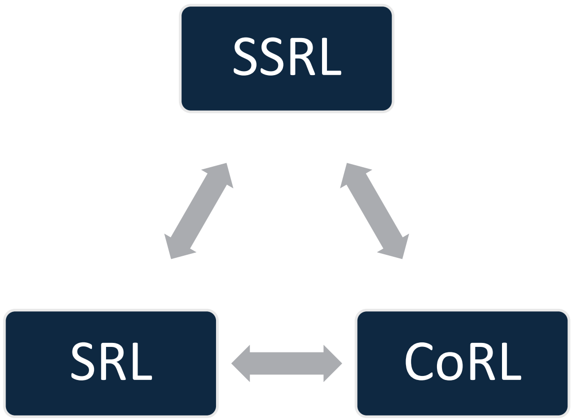

Figure 2: Illustrating the synergy between the three modes of regulation of learning: self-regulation (SRL), co-regulation (CoRL), and socially shared regulation (SSRL).

2.3.4 Collaborative Learning and interdisciplinarity

Having outlined the various components of collaborative learning as part of interdisciplinary project-based courses, the question arises "what happens when they are all put together?". Based on my reading of the literature I argue that the impact of interdisciplinarity on SoRL has been undertheorized, with the majority of previous studies on SoRL only focusing on monodisciplinary groups (e.g. Malmberg et al., 2015; Panadero et al., 2015). Similarly, very few studies have examined SoRL and collaborative learning over the course of a project. The few that I have found tended to focus on one aspect of SoRL. Kim and Lim (2018) looked at socially shared metacognitive regulation in monodisciplinary groups, and while Bakhtiar and Hadwin (2020) investigated interdisciplinary groups over the course of a project, they only focused on the regulation of motivation. As I outlined earlier, motivation and metacognition are only two aspects of learning that can be regulated, so there is a need to consider the other aspects and learning overall.

There are some potential issues that we might expect interdisciplinary groups to experience. One potential challenge is finding common ground and a shared understanding of the problem their project is to solve (Arthars et al., 2024). This could be exasperated by group members' disciplines having their own terminology, epistemology, and procedures (Buanes & Jentoft, 2009). The establishment of common ground and a common vocabulary is essential for a group to achieve interdisciplinarity and integration of knowledge and perspectives (Repko, 2007). A common understanding and shared perspective should also lead to all group members viewing problems the same way which should lead to more satisfaction within a group and better regulation (Melzner et al., 2020).

Another important element is whether group members take a collectivist approach or individualist. Collectivists are more committed to both collaboration and interdisciplinarity and are more positive towards both (McCance & Blanchard, 2024). Conversely, individualists or members with low collectivism are more concerned with their own learning and goals. This aligns with Greisel et al.'s (2023) findings, where groups with mastery goals were more likely to engage in CoRL and SSRL, while those with performance goals only engaged in SRL and SSRL. The conclusion they drew was that groups and individuals with performance goals were only interested in helping themselves and their own learning. Mastery goals are concerned with gaining knowledge, skills, and understanding, whereas performance goals are concerned with attaining a certain grade, or to do better compared to others (Pintrich, 2000).

While there are potential pitfalls, interdisciplinary groups also provide opportunities for CoRL as members could take an expert role for the group on topics or tasks related to their own discipline. Similarly, different perspectives can also lead to unique solutions for complex problems.

3. Methodology

My PhD journey has seen a change in my epistemological, ontological, and theoretical perspectives, which is reflected in the methods I have used throughout the four papers of this thesis. In this chapter, I will outline the epistemology that I align with and describe the context and settings of the four papers. I will then describe the methodologies of each paper, which will include a description of how the papers influenced each other and the choices that were made in terms of methods used. Finally, I will introduce the methodological contributions of this thesis.

3.1 Research Philosophy

Reflecting on my master's thesis, its methodology (I used quantitative methods), and my theoretical perspective on research, I would label my former self as being a positivist. According to Bernhard and Baillie (2016), this isn't unusual for someone with my background, as they note that many engineers moving into the field of EER lean heavily towards positivism or post-positivism due to its prevalence in STEM. Positivism asserts that there is a truth or reality that can typically be described or revealed using empirical methods (Crotty, 1998). Crotty (1998) notes how post-positivism expands upon positivism by considering its weaknesses, including the inevitable influence the researcher's perspective will have on the study. Post-positivists "admit that, not matter how faithfully the scientist adheres to scientific method, research outcomes are neither totally objective nor unquestionably certain" (Crotty, 1998 p.40). Positivism and post-positivism are often heavily associated with quantitative data (Bernhard & Baillie, 2016). However, these research paradigms are not limited to one method and can equally utilize qualitative methods (Crotty, 1998). Bernhard and Baillie (2016) suggest that when engineers move into EER they tend to continue to align with positivism and post-positivism, associating them with rigour and hoping that their former peers will see value in their research. On reflection, I also previously equated positivism with rigour and reliability.

In terms of epistemology, "positivism is objectivist through and through" (Crotty, 1998 p.28). Objectivism considers meaning to exist within objects independent of researchers, though this meaning can be revealed using the correct methods (Moon & Blackman, 2014). As someone with an engineering background, I can understand the appeal of positivism and objectivism. During my undergraduate programs and early in my research career, this would have been how I saw the world. However, my position began to change years later as I began to read and prepare proposals for PhD positions. I began to conclude that positivism and objectivism would be insufficient for the questions on learning that I wished to ask. At this point I had not chosen an alternate perspective for my research and could see positives and negatives in numerous perspectives outlined in the literature. However, I knew that I had to reconsider my initial perspectives.

My readings on the topic led me to two alternative theoretical perspectives: pragmatism and constructionism. I was drawn to constructionism as it views knowledge, and meaning, as something we construct as we interact and decipher the world around us. In its true sense it is neither purely objective or subjective but looks at the interaction between subject and object (Crotty, 1998). This suited me as I don't see myself as aligning with either objectivism or subjectivism. Constructionism can be used to provide contextual solutions to complex problems (Moon & Blackman, 2014). I based my licentiate thesis on a constructionist perspective with (social) constructivism as my theoretical perspective as it considers how individuals interpret the world and construct their individual meaning (Moon & Blackman, 2014). While they share a similar name there is a key difference between constructionism and constructivism. Constructionism is primarily focused on the knowledge built by interactions between individuals, in other words the group's knowledge, while constructivism is focused on the knowledge built by the individual based on their interactions with others (Crotty, 1998). This suited my licentiate which was more centred around collaborative learning. However, I still wondered if pragmatism would be a better description of how I approached my research. My approach to research has always been to ask a question and then look for the best way to answer it (within my means and resources). As my PhD journey continued and the number of papers I was involved in increased, I began to see myself and my work as being in line with a pragmatic theoretical perspective.

I am drawn to pragmatism as I am primarily driven by research questions and look for the best tools I can use to answer them, which aligns with how Creswell and Creswell (2018) describe it. Thus, by working within a pragmatist paradigm, I am not limited to any one method of data collection or epistemological perspective (Cohen et al., 2011; Cresswell & Gutterman, 2021). This has led to misconceptions about pragmatism being "philosophically neutral" or "a non-philosophy" that only takes a superficial approach to research methods and philosophies, which diminishes the contributions it can make (Cassell et al., 2018, p3). Cassell and colleagues contest this and point out that pragmatism is unbound by protocols as it considers events and people to be in a state of progress or transformation. Pragmatism takes its own ontological approach to truth and reality, seeing them as relative to the context and methods used to reveal them (McCaslin, 2008). In epistemological terms, pragmatism does not choose a side in the classic duality of objectivism and subjectivism and instead takes a more holistic approach between the two (Cassell et al., 2018; Creswell & Creswell, 2018). By avoiding that dichotomy, it appears to take a similar position as constructionism, with Crotty (1998) even labelling Dewey and pragmatism's early incarnations as a combination of constructionist and critical. It is probably no coincidence then that I have been drawn to both pragmatism and (social) constructionism in the past.

While some might see my choice of pragmatism to be cowardice in not "nailing my colours to the mast", I consider it to be a freeing and open approach to research. Perhaps pragmatism appeals to me because of my engineering and technical background and the inherent flexibility it provides in allowing me to choose research methods without being beholden to particular ones due to epistemology. This pragmatism is reflected in the choices I have made in the research design of my papers and this thesis. For example, when investigating ways to examine SoRL, I spent considerable time exploring different options for both quantitative and qualitative methods of data collection. I will discuss some of my decisions in relation to these methodological choices in Section 3.3.

3.2 Research Context

Before discussing the methods used in the four papers, I will first provide a brief description of the setting for most of the papers in this thesis. Chalmers University of Technology operates under the Swedish education system offering bachelor's, master's, and doctoral degrees. To clarify for readers unfamiliar with the Swedish systems, the bachelor's degrees are three years in duration (and would be classed as "ordinary" bachelor's degrees outside of Sweden). The master's degrees are two years in duration and should be considered "taught" masters (as opposed to research master's which can be found in the UK and Ireland). Chalmers is considered a technical (or engineering) university with 13 departments and only offers degrees in disciplines that fall under the umbrella of STEM.

In the introduction chapter I mentioned that Tracks have funded my PhD studies, and I refer to Tracks courses numerous times in this thesis. However, I am aware that many readers might not be familiar with Tracks, so I will provide a brief description of Tracks and its courses. Tracks is a 10-year initiative which offers students (and in some cases alumni and professionals) an opportunity to take part in interdisciplinary project-based courses. All Tracks courses are electives that sit outside the regular curricula of all of Chalmers departments. The entry criteria for courses vary, but they can be open to students from the bachelor's to PhD level, with some also allowing alumni and professionals to attend. The courses have a shorter timeline from proposal to delivery than courses for regular degree programs. Once accepted, each Tracks course can have up to three iterations, after which the teachers of the course need to apply to run additional iterations. While the content and design of Tracks course can vary significantly, all courses share some common features. They must provide some lectures or classes for foundational knowledge, there must be a group project (these are typically 4+ weeks in duration), and the courses must be related to ongoing research or societal challenges. These requirements made Tracks courses an ideal resource for my research on interdisciplinary PjBL and collaborative learning.

Participants in three of the papers had different levels of involvement in Tracks, and an outline of the various participants' backgrounds can be found in Table 1 along with the research questions and data collection and analysis methods. The student participants for **Papers 2, 3, and 4** were all students at Chalmers, with **Paper 2** also featuring professionals from industry that had enrolled onto a Tracks course. All of the student participants (and all of the students in their groups) in **Papers 2 and 3** were enrolled on master's programmes when taking the Tracks courses the papers are centred on. The courses in **Papers 2 and 3** were 7.5 credits and minimum two months in duration. The Chalmers teachers that took part in P**aper 1** had experience designing and delivering Tracks courses.

Table 1: An outline of the research questions, methods of data collection and analysis, participants, and education level of participants (where applicable) for each paper.

Paper	Research Questions	Method of Data Collection & Analysis	Participants	Education Level
1	How do teachers conceptualize the nature of interdisciplinary engineering education? What competencies do teachers perceive students gain from interdisciplinary engineering education?	Semi-structured interviews (in-person) Thematic analysis (inductive coding)	Teachers of interdisciplinary project-based courses	N/A
2	What epistemic practices do the three types of groups employ – and how are these epistemic practices enacted – in interdisciplinary project-based learning? How do the students and professionals position themselves, each other, and the project?	Semi-structured interviews (online) Thematic analysis (theoretical coding)	Students & Professionals enrolled on a Tracks course	Master's & above
3	The paper aimed to investigate how interdisciplinary groups regulate their learning during project-based courses and what factors can aid or hinder a group's regulation.	Semi-structured interviews (online) Thematic & Narrative Analysis	Students enrolled on Tracks courses	Master's
4	What challenges do students experience during UREs? What coping strategies do students use in response to those challenges?	Reflective writing Thematic analysis (inductive coding)	Students taking part in a URE	Bachelor's

The participants in **Paper 4** were all third-year bachelor's students taking part in UREs, which were run by Chalmers' Genie initiative over the summer of 2020. The programme's aim was to give undergraduate students an opportunity to participate in paid research. Students were placed into (student only) groups and assigned research projects. It was "project-only" with no classes for basic knowledge provided apart from instructions on how to use lab equipment where needed.

3.3 The development of the papers and their methodologies

The order in which I discuss the papers in this section might seem unusual to the reader as I begin with **Paper 4**. I do this because the methodological development of the papers occurred in a different chronological to their conceptual order. The conceptual structure of this thesis begins with the concepts of interdisciplinarity and PjBL, before then examining how they influence or affect collaborative learning and SoRL. However, they were written in the opposite order with **Paper 4** written first and **Paper 1** last.

From a pragmatist perspective, when choosing a method of data collection and analysis for a study I am unbound by epistemological ideals. Thus, when designing a study, my only question is "what is the best method to employ to examine this phenomenon or to answer this research question?". Ultimately, I chose to take a qualitative approach for my papers as it provides rich, deep data and allows for "an in-depth exploration of a central theme" (Creswell & Guetterman, 2021 p240). I was also attracted to methods that place the participants and their experiences at the centre of data collection. That is not to say we did not consider quantitative or mixed methods – we did. However, after exploring and considering quantitative methods, it became apparent that they would not be suitable for the questions we were trying to answer. In the following sub-sections I will outline the data collection and analysis methods used in all four papers. I will also describe the contributions my papers made towards methodology in the field of engineering education. For clarity, Table 1 also lists the research questions, and the methods of data collection and analysis used for each paper.

3.3.1 Data Collection Methods

Reflective writing was chosen as the method of data collection for **Paper 4**, which examined the challenges students faced when taking part in UREs. The advantage of reflective writing is that its role is not limited to data collection as it can also contribute to the students' learning (Jasper, 2005). From a learning perspective, reflective writing helps students access knowledge and experiences and with reflection they can gain a deeper learning (Scanlan et al., 2002). It also aids students in making the connection between theory and practice. Students describing how they understand a topic will help them make meaning of their experiences and link them to what they have previously read or covered in class (Scanlan et al., 2002). The act of reflecting upon their actions and thinking, as well as those of others, will help facilitate critical thinking (Jasper, 2005; Kathpalia & Heah, 2008). The act of reflection is also one of the phases in Zimmerman's model of SRL (Zimmerman & Moylan, 2009) upon which my theoretical framework of SoRL is based.

From a pragmatic perspective, reflective writing as a data collection method has particular strengths for the study of groupwork and the regulation of learning. Previous studies that utilize reflective writing (e.g. Hoover, 1994) demonstrate its ability to gain access to students' motivations, goals, thinking and feelings along with descriptions of events they were part of. It also allows us to gain an insight into the students' use of metacognitive, cognitive, and SRL strategies (Wallin & Adawi, 2018). Reflective writing also gives students' ownership of their own story as they decide what should be included (Jasper, 2005). This will require students to order their thoughts and place them, and events, in sequence.

To this end, the reflections need to be on specific topics or experiences for them to be useful in answering the research question. Additionally, students are most likely to remember incidents or episodes that came with strong emotions, positive or negative (Scanlan et al., 2002). A way to counteract these potential issues is through scaffolding, using prompts or open-ended questions that elicit an “I” or “we” response, or asking students to complete reflective statements, such as “My biggest challenge was...” and “I solved it by...” (Kathpalia & Heah, 2008), or the students can be given a series of writing tasks (Hoover, 1994). For **Paper 4** we opted to use open-ended questions as they provide focus by requiring an answer, but they also allow the student to clarify or elaborate on their answer (Cohen et al., 2011).

While the use of reflective writing was successful for **Paper 4**, there are some limitations to the method. Reflective writing is a skill that needs to be practiced and can be difficult for inexperienced students. While some programmes (such as Nursing in my old university) frequently require students to engage in reflective writing, it is less common on engineering programmes. Collecting students' reflections can also be challenging as it can be considered a self-administered survey, which according to Cohen et al. (2011) can mean low response rates.

When planning for **Paper 3,** which examined student groups' SoRL during a project, we considered using reflective writing for data collection as part of a mixed methods approach. The initial intention for the paper was twofold. First, we would collect three rounds of reflective writing using open-ended questions with the last including a quantitative survey in the form of a questionnaire. This would be followed by interviews with students. The open questions for all three rounds of reflective writing were designed and a pre-existing questionnaire for CoRL was selected to be added to the final round. A pretest of all three rounds and the questionnaire was conducted. However, a preliminary analysis of the data indicated that it would be insufficient in answering the paper's research question. Conversely, a preliminary analysis of the interview data revealed far more depth and richness. As the interview data was determined to better answer the research question, the decision was made to solely use that data for the paper. Interviews were also chosen as a method of data collection when planning for **Papers 1 and 2** for the quality of data they produced.

Interviews are similar to reflective writing in some respects. They are centred around an interviewee who is given ownership of their story where they can talk about what they feel is important (Doody & Noonan, 2013). One major difference between the two is the opportunity for the interviewer to clarify misunderstandings or dig deeper with further questions if something of interest is revealed (Cohen et al., 2011). We opted for semi-structured interviews as they have a structure for me (the interviewer) to follow but also allow for me to move outside of the predetermined questions to explore different themes during the interview (Alshenqeeti, 2014). Interviews allow for the interviewee to provide insight, context, and detailed responses, as well as allowing for the interviewee to ask questions on the research or for clarification (Doody & Noonan, 2013). While not an equivalent learning experience to reflective writing, interviews do allow for the interviewees to potentially benefit from self-exploration (Doody & Noonan, 2013).

After the decision to use semi-structured interviews for each paper was made, I (with the help of my co-authors) had to design interview protocols. Interview protocols provide a structure for the interview and include the introduction of the interviewer(s), a description of the study, a reminder of the interviewee's rights regarding consent, and the questions to be asked (Creswell & Guetterman, 2021). The latter is especially important as the predetermined interview questions affect the direction of the interview, and the quality of the data gathered. The questions were drawn from each paper's conceptual framework as well as my previous experiences. For **Papers 2 and 3,** this meant using Zimmerman's model of the phases of SRL as a way to ask about different phases of the project, and these phases are commonly found in SoRL literature. The questions for **Paper 3** also focused heavily on challenge episodes, which have been highlighted as an underutilized way to identify SoRL (Hadwin et al., 2017) and the interviewee's reflections on their course experiences. **Paper 2**'s interview questions also had some questions related to challenges but had more questions that directly asked about regulation and learning processes (as opposed to indirect questions in **Paper 3**). The protocol also asked the interviewee's questions on their opinions on the project, the course, and others in the class or groups. The questions for **Paper 1** used a different conceptual framework with questions influenced by the authors' previous works, such as Feng et al. (2023) and Kjellberg et al. (2023). When composing the questions, consideration was given towards the type of responses that were expected – e.g. "what do you like about X" vs "tell me 2 things you like about X" – and the type of data we wanted – e.g. factual answers, opinions, interpretations (Cohen et al., 2011). When composing and delivering the questions, I kept in mind the advice that interviewers should try to ensure the questions are neutral, and that they appear empathetic to the interviewee (Doody & Noonan, 2013). Once drafts of the protocols were completed, they were reviewed by me and the other co-authors. This often resulted in rounds of discussion and clarifications, where the questions were refined to ensure we would collect the necessary data. For **Paper 1,** we conducted a pilot interview to test our protocol. This resulted in minor tweaks to the protocol, and the interview was considered successful and included in the data analysis. For **Papers 2 and 3,** I discussed the interview protocol, and the data gathered with a co-author after the first interview. Apart from some slight rewording, no major changes were deemed necessary. The interviews for **Papers 2 and 3** were held online and recorded. For **Paper 3,** this was partly due to covid restrictions, which limited classes on campus and partly for convenience (mine and the interviewees'). Interviewees for **Paper 2** were given the option to have in person or online interviews, and all chose to be online, again for convenience. All bar one of the interviews in **Paper 1** were in person, and all except two were conducted with the first and second author (one was conducted by the second author alone and the other by the first and fourth authors).

There are however some potential issues with interviews as a data collection method, which I would be remiss for not mentioning. Interviews are dependent on memory and the interviewee's ability to recall events from the past, which means their recollections or answers can be subjective and liable to change or be influenced by other actors including myself as the interviewer (Alshenqeeti, 2014). A counterpoint, however, is that while other methods such as observations of a group working together would not be reliant on memory, they would be unable to provide insight into the group members' thoughts and motivations. For **Papers 3 and 2** the interviews were conducted a number of weeks after their Tracks courses had ended, and the questions were focused on projects that were four or more weeks in duration. So, I linked some of my questions with certain aspects or typical events in projects (e.g. how to organize work or meetings) and used clarifications and hypothetical examples to help stimulate memory. I had to be very cautious with the latter to ensure I did not influence the interviewee. Another potential issue is that an interviewee might struggle to express themselves (Creswell & Guetterman, 2021). If I suspected this was the case, I would gently probe with some questions for clarity or repeat my understanding of the answer and ask if it is correct. As I contacted the interviewees through their courses and either Chalmers' Canvas system or email system, there was a danger I would be associated with the teachers of the course or the Tracks management. For this reason, I was transparent and let them know my PhD was funded by the Tracks initiative, but I was an independent actor and was in no way involved with Tracks management or teaching. I also reassured them that their participation (or withdrawal) would have no effect on their grades or studies. This transparency was important as I did not want them to associate me with a teacher or position of power, and I wanted them to speak freely (Brinkmann & Kvale, 2015). These issues were not so prevalent with **Paper 4** as the teachers being interviewed were expressing their understanding, opinions, and experiences in relation to their teaching of interdisciplinary project-based courses. They were therefore not asked about specific instances or episodes in their past.

The interviews for **Paper 2 and 3** (and one from **Paper 1**) were all held online, which De Villers et al. (2022) cite as a potential issue. They warn that there is a potential that the interviewee's might not be familiar or comfortable with the technology being used. This was taken under consideration but was judged to not be an issue as the interviewees often requested online interviews. All interviewees also reported that their groups held regular online meetings which, to me, suggested that they were already adapt and familiar with the technology. Similarly, my background meant I was experienced and comfortable with the medium from team meetings and delivering classes online (and by P**aper 2** I was also experienced in conducting online interviews). However, as I reflect on the interviews from P**apers 1, 2, and 3** I can acknowledge that it is more difficult to get a "sense and feel" for the interview and the interviewee when it is conducted online versus in-person. That is not to say that there are no redeeming features for online interviews. According to De Villers et al. (2022), online interviews are often preferrable to in-person ones as they are both convenient and the interviewee may feel more comfortable giving an interview from their own home or office.

3.3.2 Data Analysis Methods

Due to its nature, qualitative data relies on the authors of the study to interpret it and make sense of the findings (Cohen et al., 2011; Creswell & Guetterman, 2021). This makes the process of analysis quite personal to the authors conducting it as they make judgements and interpretations based on their own theoretical perspectives and knowledge. The first step is typically to organise and prepare the data for analysis (Creswell & Guetterman, 2021). This was straightforward for **Paper 4,** as it used reflective writing as a data collection method with students submitting their reflections in Word or pdf documents. So, the documents only needed to be gathered in one place and checked to ensure they were readable. The other papers all used semi-structured interviews for data collection and so required some extra steps before the analysis could begin. For **Papers 2, and 3,** the audio files from the online interviews were transcribed using Word's inbuilt transcription tool and then manually checked by myself. For **Paper 1,** a transcription tool licenced by Aalto University was used to generate the initial transcripts. These were then manually checked against the original recordings which also allowed us to become familiar with the data. Once all the data for each paper had been gathered (in text format) and verified, we began analysing and interpreting it. A graphical representation of the different analysis processes can be found in Figure 3.

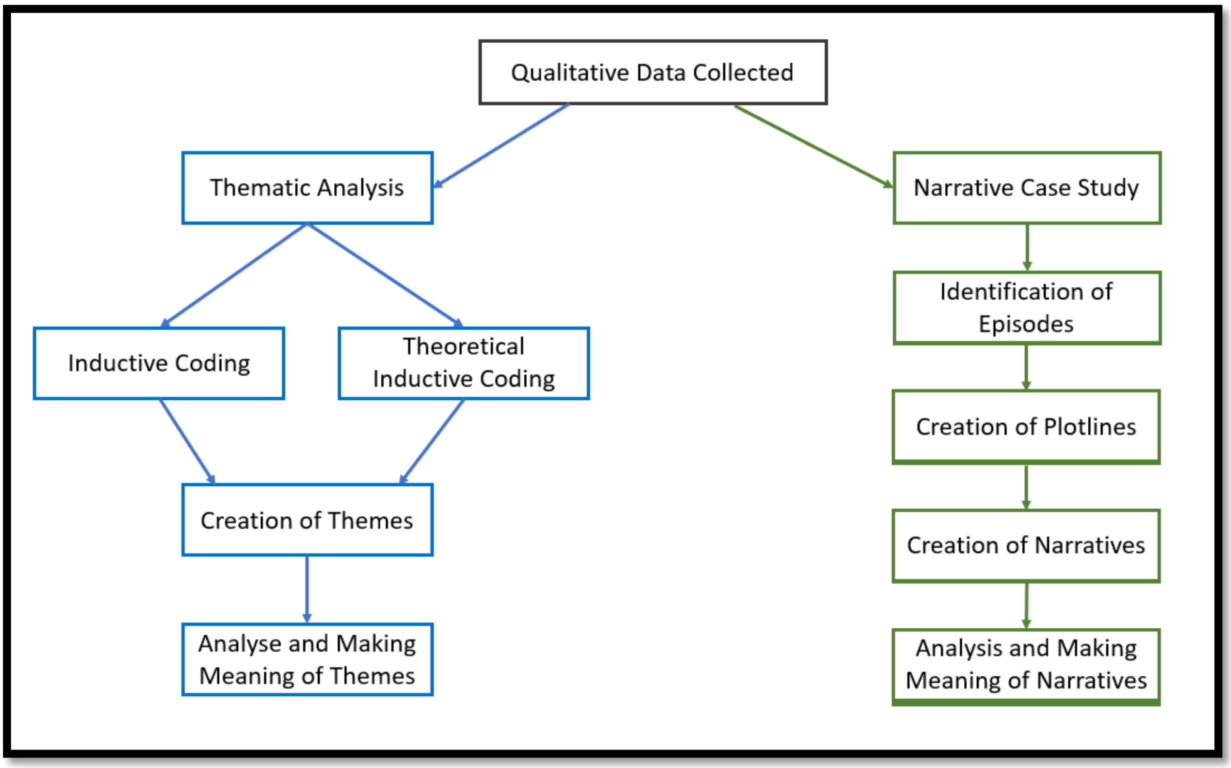

Figure 3: A graphical representation of the different forms of analysis performed on the different papers.

Thematic analysis was chosen for data analysis for **Papers 1, 2 and 4**, but in slightly different ways. The method of analysis chosen for **Paper 3** differed from the other papers and will be discussed separately later. As a method, thematic analysis is flexible and not tied to any one theoretical framework (Braun & Clarke, 2006). This allows the researchers to examine the data through their own theoretical framework to analyse experiences and perspectives (Lochmiller, 2021). We found this flexibility aligned with our aims for **Papers 1, 2 and 4** which were to capture participants' experiences and perspectives while remaining consistent with our pragmatic paradigm.

Unfortunately, despite the widespread use of thematic analysis in qualitive research, there is a significant amount of ambiguity in how it is defined and practiced (Lochmiller, 2021).

Therefore, to avoid uncertainty, it was decided to apply thematic analysis according to the works of Braun and Clarke (2006) as they have written about the method in numerous publications and are highly cited for it. This method of thematic analysis is composed of six phases: (1) familiarizing yourself with your data; (2) generating initial codes; (3) searching for themes; (4) reviewing themes; (5) defining and naming themes; and (6) producing the report. Though the six phases are presented linearly, the analysis is iterative, with one moving through the phases as required (Braun & Clarke, 2006).

The objective of thematic analysis is (as the name suggests) to identify themes from patterns within the data (Braun & Clarke, 2006). To do this, one will first read through the data and develop codes, which is usually done for a number of iterations, with codes being created, discarded, or conjoined, and renamed. Eventually, codes are grouped together to form themes that are relevant to the research question (Braun & Clarke, 2006). Clarke and Braun do, however, mention how the research questions themselves can evolve during the different iterations of thematic analysis (Clarke & Braun, 2014). While all forms of thematic analysis involve roughly the same process of data --> codes --> themes, they differ in how the codes are developed. The two most prevalent forms are deductive and inductive, with some researchers promoting a hybrid approach between the two (Swain, 2018). An inductive approach was taken for **Papers 1, 2**, and **4,** although **Paper 2 (**and the early stages of **Paper 3**) could be considered what Braun and Clarke (2006) call a “theoretical” thematic analysis. A theoretical thematic analysis is also inductive, but there are some subtle differences between it and a “pure” inductive approach. These differences lie mostly in the role of theory in the analysis. Theoretical thematic analysis is “guided by an existing theory and theoretical concepts (as well as by the researcher’s standpoint, disciplinary knowledge and epistemology)” (Braun & Clarke, 2013 p.175). Inductive thematic analysis is more exploratory and “is not shaped by existing theory (but analysis is always shaped to some extent by the researcher’s standpoint, disciplinary knowledge and epistemology)” (Braun & Clarke, 2013 p.175). Another difference between the two is the role of research questions in relation to the analysis. The research questions are more concrete and backed by a theoretical framework in theoretical thematic analysis but are more malleable and likely to evolve during an inductive thematic analysis (Braun & Clarke, 2006). Thus, for **Papers 1 and 4**, multiple rounds of coding were performed, where patterns and connections were looked for without preconceived theories in mind, and later in the analysis we looked to the literature to see where the themes we formed lay in the theoretical landscape. **Paper 2** used SoRL theory in the analysis in a way I have not previously seen and so I will provide more details about it in another sub-section.

3.3.3 Contributions to Methodology

Two of the papers in this thesis (**Papers 2 and 3**) make contributions to the methodological landscape, which I will outline in this section. When planning for **Paper 3,** our goal was to examine and document SoRL within groups taking part in interdisciplinary PjBL. Researchers have taken a number of different approaches to record and study SoRL (Hadwin et al., 2017). However, from our reading of the literature it became apparent that there is still a lot of exploration for the best method of studying the phenomenon. During the design of the study, when we decided to collect only qualitative data, we similarly had to choose how to analyse and present the data and findings. As we wanted to examine and document SoRL as it developed over a project, we opted for a comparative narrative case study design. This would allow us to collect data from participants, which would be formed into narratives about common events that would then be analysed and interpreted. Narratives allow for events to be presented chronologically and give voice to the participants' stories and experiences (Creswell & Guetterman 2021; Jovchelovitch & Bauer 2000).

The first round of analysis identified and coded instances of regulation, using Miller and Hadwin's (2015) table of regulation and Zimmerman's (2000) model of self-regulation as an analytical framework. The analysis also coded for factors that might affect groups or regulation (e.g. someone didn't have much experience in the subject matter). Following this, the formation of narratives took several steps. First, the regulation episodes for each interview were clustered together to tell the story of that project, e.g. all regulation episodes related to the beginning of the project or planning were put together. All interviews were individual, but some of the interviewee's had been in the same project groups so their interview data was combined to tell the group's story. Next, all the clusters were condensed into readable episodes. Narrative plots were then formed to tell the story of each group, which helped to decide which episodes to keep (Jovchelovitch & Bauer, 2000). Next, narratives were formed and were checked against the original episodes and interviews to ensure consistency. At this point, the narratives for three groups were dropped due to restrictions on space/word count. When choosing which ones to keep, preference was given to narratives that were formed from more than one interviewee, and which had more unique episodes of SoRL. The three remaining narratives were further refined and presented as a series of episodes or stories. Each episode was accompanied by a short interpretation based on the paper's theoretical lens. Narratives help to connect and resonate with readers by tapping into the principles of storytelling, while also providing a way to derive meaning from the data (Creswell & Guetterman 2021; Jovchelovitch & Bauer 2000). Our use of narratives allowed us to successfully present and analyse the stories of the groups' regulation. It was a surprise then when we were unable to find other studies on SoRL that employed narratives, which suggests this is an under-utilised method for research on this topic.

Paper 2 examined a Tracks course that had both master's students and professionals from industry enrolled on it. Two research questions were formulated for the study, and this section is focused on how we addressed the first of those questions: *What epistemic practices do the three types of groups employ – and how are these epistemic practices enacted – in interdisciplinary project-based learning?* From a pragmatic perspective, I began to investigate and consider ways to identify these practices. When reading through literature on collaborative learning and SoRL a thought occurred. Previous literature on SoRL appears to be focused on documenting it (e.g. Rogat & Linnenbring-Garcia, 2011) or looking for triggers of regulation (e.g. Ucan & Webb, 2015). However, if we consider that SoRL is a necessary process for collaborative learning to occur (Summers & Volet, 2010), then perhaps we can use it to identify a group's epistemic practices. The approach would effectively reverse what we did for

Paper 3. Rather than look at group actions and determine if it was CoRL or SSRL, I would look for examples of regulation to help record how groups engage in learning. This was done through two steps: in the design of the questions for the interviews, and in the analytical framework used in the data analysis.

When composing the interview questions, we once again used Zimmerman's (2008) three phases of SRL as a base, which reflect the three phases of a project (goal setting & planning, monitoring & implementation, reflection & evaluation). Additional questions on regulation sought to identify triggers and examples of CoRL and SSRL. Further questions explored groups organization, their response to challenges, and their thoughts on their learning experiences.

A theoretical thematic analysis was performed on the data, with SoRL making up part of the analytical framework. The analysis successfully revealed many epistemic practices and examples of processes that indicate an engagement in collaborative learning. It also provided insight into the participants' goals, motivations, and the influence they felt group members had on each other's learning. The analysis also found instances of SoRL which supported and expanded on previous findings of regulation of learning in both the literature and **Paper 3**. Based on this experience I feel that there is great potential in the use of SoRL as an analytical tool to identify collaborative learning, epistemic practices, and a way to study groupwork.

4. Summary of the Papers

Having outlined my theoretical and methodological frameworks, I will now provide a summary of the four papers that this thesis is based around. The summaries will provide the background, methodology, and results for each paper. The aim of this chapter is to provide the reader with a basic knowledge of all four papers. I will therefore keep the summaries concise as the full papers are appended to this thesis.

4.1 Paper 1

Title: *Interdisciplinarity as a travelling concept: Teachers' conceptions of the nature and role of interdisciplinary engineering education*

In recent years, there has been an increased interest in universities offering interdisciplinary project-based courses to engineering students. The teachers of these courses play a vital role in their design and delivery. Their understanding of interdisciplinarity and interdisciplinary education can therefore have a direct impact on the courses they teach. Additionally, we argue there is a dearth of studies within engineering education that attempt to theorize what interdisciplinarity means within the field itself. The paper sets out to examine how teachers understand interdisciplinarity and what they believe students will gain from interdisciplinary engineering education. To do this we presented the following research questions:

RQ1: How do teachers conceptualize the nature of interdisciplinary engineering education?

RQ2. What competencies do teachers perceive students gain from interdisciplinary engineering education?

The base for this paper was a qualitative research design with 18 teachers of interdisciplinary engineering courses interviewed across three Nordic universities (Aalto, Aalborg, and Chalmers). The interviews were semi-structured and all were in person except for one. An inductive thematic analysis was performed on the data with themes formed for each of the research questions.

On the teachers' conceptions of interdisciplinarity we identified two themes: *epistemic interdisciplinarity* and *social interdisciplinarity*. Each of which had two sub-themes, see Table 2.

Table 2: Teachers' conceptions of the nature of interdisciplinary education

Epistemic interdisciplinarity	Social interdisciplinarity
Bridging knowledge silos	Interacting between people from different disciplines
Building a web of interconnected knowledge	Envisioning cooperative roles

Epistemic interdisciplinarity sees interdisciplinarity as knowledge integration and conceptual understanding. Here disciplines themselves are considered to be standalone entities akin to books or banks of knowledge, competencies, and culture. By contrast, social interdisciplinarity sees interdisciplinarity as occurring through collaboration between individuals. Disciplinary knowledge and competencies are seen as existing within individuals.

Three themes were identified when analysing the teachers' conceptions of the competencies to be gained from interdisciplinary engineering education: *disciplinary competencies*, *cognitive and metacognitive competencies,* and *transversal competencies.* All three themes and their sub-themes are presented in Table 3.

Table 3: Teachers' conception of the competencies gained from interdisciplinary education.

Disciplinary Competencies	Cognitive & Metacognitive Competencies	Transversal Competencies
Gaining knowledge of or from other disciplines	Understanding and considering multiple perspectives	Transversal skills
Creating new knowledge or skills	Thinking skills, open-mindedness, and broader perspectives	
Learning more about your own discipline	Ability to engage in problem-solving/creating solutions	

Disciplinary competencies are those which are directly related to the acquisition or development of disciplinary knowledge and skills. Interdisciplinary education was also seen to result in cognitive and metacognitive competencies which pertain to problem solving, perspectives, and ways of thinking. Finally, teachers also cited transversal competencies as one of the benefits of interdisciplinary education. This may be due to the format of interdisciplinary education the teachers implemented i.e. project-based courses.

The findings demonstrate how there is no single conceptualization of interdisciplinarity among engineering teachers. Indeed, the conceptualizations they provided align with multiple definitions of interdisciplinarity from outside of engineering education. We therefore used

Bal's (2002) notion of "travelling concepts" to frame interdisciplinarity in engineering education. Travelling concepts are concepts that assume different meanings as they metaphorically travel between and within disciplines.

The findings also indicated that teachers were more homogeneous in their conceptualizations of the competencies to be gained from interdisciplinary engineering education. This suggests teachers are more familiar with, or more used to discussing, the benefits of interdisciplinarity over what the concept means.

4.2 Paper 2

Title: *Engineering students and professionals as co-learners: Epistemic practices and positioning*

In addition to universities introducing interdisciplinarity into engineering education, there is growing interest in also incorporating non-academic perspectives. One example is the enrolment of professionals and students in interdisciplinary project-based courses. This paper examines the epistemic practices and perspectives (positionings) of participants of such a course. To frame this combination of students and professionals as co-learners, we borrowed Repko and Szostak's (2017) concept of "interdisciplinarity plus". Interdisciplinarity plus expands upon interdisciplinarity to allow for a joining of academic and non-academic actors.

The Tracks course chosen to be the focus of this study had both engineering master's students and engineering professionals enrolled on it and contained three types of project groups: students only, professional only, and mixed groups. The study was guided by the following research questions:

RQ 1: What epistemic practices do the three types of groups employ – and how are these epistemic practices enacted – in interdisciplinary project-based learning?

RQ2: How do the students and professionals position themselves, each other, and the project?

A qualitative approach was taken with semi-structured interviews conducted with members from different group types. Three students were interviewed (two from different student groups, S1 and S2, and one from a mixed group, M2), and five professionals (two from different professional groups, P1 and P2, two from one mixed group, M1, and one from the other mixed group M2). All interviews were online, and all but one were one-to-one. A thematic analysis of the data saw the formation of themes for each research question.

Five themes were identified in relation to the epistemic practices that the groups engaged in (RQ1): *co-constructing a project focus, coordinating actions, monitoring progress and quality, supporting learning within groups,* and *building group cohesion and interdisciplinary capacity*. An overview of the themes is provided in Table 4, which includes descriptions of how each group enacted each practice.

Table 4: The five epistemic practices identified and their enactment by group type (RQ1).

Epistemic practices (*what* aspect)	Enactment of the epistemic practice (*how* aspect)		
	Student groups	*Mixed groups*	*Professional groups*
Co-constructing a project focus	Based on a single proposal Based on shared interest in proposed topic	Based on pooling of multiple proposals Based on range of individual interests, experiences, and resources	Based on selection from multiple proposals Based on ideology: Reflect industry issues Teach students (P1)
Coordinating actions	Meetings for synchronous coordination: review and decide on action plan Less time restrictions: available to meet on weekdays, weekends and in person or online Shared online document for asynchronous coordination	Meetings for synchronous coordination: review and decide on action plan More time restrictions: only available to meet on weekends and online Shared online document for asynchronous coordination	Meetings for synchronous coordination: review and decide on action plan More time restrictions: only available to meet on weekends and online Shared online document for asynchronous coordination
Monitoring progress and quality	Synchronous monitoring of progress in meetings Asynchronous monitoring of progress (contribution) through online document No quality checks (S2) Surface quality checks (S1)	Synchronous monitoring of progress in meetings Surface quality checks (M2) Deep quality checks (M1)	Synchronous monitoring of progress in meetings Deep quality checks
Supporting learning within groups	Support on request by reading up on the issue (S2) Actively checking if support is needed (S2) Teaching and knowledge sharing by all group members (S1) Creating a shared understanding	Support on request by reading up on the issue (M1) Teaching and knowledge sharing by all group members (M1) Explanations by professionals only (M2) Creating a shared understanding	Support on request by reading up on the issue (P2) Teaching and knowledge sharing by all group members (P1) Creating a shared understanding
Building group cohesion and interdisciplinary capacity	Familiar with each other Narrower disciplinary background as group	Unfamiliar with each other Broader disciplinary background as group No reported attempt to get to know each other (M2) Meeting to get to know each other (M1)	Familiar (P1)/Unfamiliar (P2) with each other Broader disciplinary background as group Familiar with project management methods

Note. When an entry is specific to a group their name is attached to it.

While the three group types engaged in similar epistemic practices, there were some significant differences in how they enacted these practices. Most notable was that all three group types used different methods to select their project topics. Student groups held an advantage over mixed and professional groups in that they had more flexibility when arranging meetings and could meet in person. Student groups were also more active in monitoring members but were less stringent in checking the quality of their project work.

Two themes were identified in relation to how the students and professionals positioned themselves, each other, and the project (RQ 2): *the partnership* and *the project.* An overview of both themes is provided in Table 5, which includes descriptions of how professionals and students positioned themselves, each other, and the projects.

Table 5: An overview of how students and professionals positioned their partnership and the project (RQ2)

Area of positioning	**Positioning**	
	Students	*Professionals*
The partnership	Positioned *professionals* as: • Having a forthright mindset • A source of industry knowledge and experiences • Having a professional network • Equal partners • Their occupation over qualification Positioned themselves/other *students* as: • A source of academic knowledge and skills	Positioned themselves/other *professionals* as: • A source of industry knowledge and experiences • Having access to a professional network • Their occupation rather than qualification Positioned *students* as: • Having an inquisitive mindset • A source of academic knowledge and skills • Equal partners
The project	Positioned the project/course in terms of its *value* as: • An interest-driven undertaking • A learning driven undertaking Positioned the project in terms of its *nature* (practices enacted) as: • Same as regular course projects	Positioned the project/course in terms of its *value* as: • An interest-driven undertaking • A career-driven undertaking • A learning driven undertaking Positioned the project in terms of its *nature* (practices enacted) as: • Different to regular industry projects (M1 & M2) • Same as regular industry projects (P1 & P2)

Note. When an entry is specific to a group their name is attached to it.

Students and professionals positioned themselves and each other in similar ways. Students as sources of academic knowledge and professionals as sources of industry knowledge and connections. Both saw the other as equal partners and as having complimentary skills and mindsets. Students and professionals saw value in having the other in the same group and classrooms. Additionally, all participants identified students with the discipline they were studying; however, professionals were mainly identified in terms of their careers. Suggesting that after leaving the academic environment professionals themselves begin to identify less with the discipline their degrees were in.

All participants saw the project (and course) as an interest-driven and learning driven undertaking, though professionals also saw it as beneficial to their careers. Students reported they worked on the project as they would have done for previous projects, though professionals were split on whether their practices were the same as for industry projects. However, those that said it was not the same stated it was due to the role they took in the project rather than the actual organization of the work (which they considered to be the same).

The findings from the paper highlight how master's students will engage in similar epistemic practices as professionals. Similarly, learning (rather than simply passing) was an important goal and source of motivation for both students and professionals. All groups engaged in practices that indicate collaborative learning and SoRL, though there was an incident where a participant opted to not engage in regulation of learning due to unfamiliarity with other group members.

4.3 Paper 3

Title: *Social Regulation of Learning in Interdisciplinary Groupwork*

When exploring studies on SoRL we noted few that examined groups' regulation over the course of a project. Often studies would examine groups taking part in an activity. While this allows for a detailed observation of the group members' actions and identification of regulation, it does not consider how this might change over time. There are even fewer studies that also look at interdisciplinary groups or groups working on an interdisciplinary project. As Tracks courses are interdisciplinary project-based courses they offered an opportunity to address this gap. This paper aimed to investigate *how interdisciplinary groups regulate their learning during project-based courses* and *what factors can aid or hinder a group's regulation.*

A qualitative approach was taken with a narrative case study design. Students from three Tracks courses were interviewed. They represented three project groups. The results were presented in the form of narratives which told the story of each group through episodes that were interspersed with interpretations that highlighted the regulation with each episode. Please note this paper uses the term supervisor as that was how the students described them.

Group 1 engaged in SSRL in the planning phases, however intervention from a teacher resulted in disagreements among the group which resulted in aggressive CoRL where members would try to convince the teacher to back their ideas and force the rest of the group to comply. There were disagreements within the group which were attributed to their different cultural backgrounds, personalities, disciplines, and their unfamiliarity with each other and the project topic. As time went on and the group became more familiar with each other and the topic they were more successful in engaging in SSRL. Their project was scaffolded by weekly class presentations where all groups in the course were required to present their work and their progress in terms of their original plan. This helped ensure effective monitoring and evaluation of their work.

Group 2 were quite successful in terms of regulation. They engaged in SSRL in the formation of a plan, but then decided it was too ambitious and changed it to something they felt was more achievable. The group opted to split tasks among themselves and would share their results before each meeting where they would then discuss them. Meetings were where they monitored progress and asked questions if something was unclear. Members sometimes took the lead in a topic they specialised in, but all decisions still required consensus within the group. Group discussions were held when an issue came up e.g. a member becoming stuck on a task. An error in monitoring was realised late in the project when their work did not align with the original plan. Ultimately the group was disappointed with the completed project. This was partly due to covid-19 campus restrictions which hampered their data collection, and partly because they felt they could have done something more challenging.

Group 3 made a concerted effort in the beginning to get to know each other and to decide on what project they wished to do. They preferred to work together, but lab requirements meant they often had to split into sub-groups to complete tasks. They would update each other regularly by walking between labs and by having weekly meetings. The group used group discussions to solve any issues that arose e.g. a member struggling to understanding a concept. Meetings were also used to monitor and evaluate the work and to plan the next tasks/actions. For their final report they worked on their own parts but read each other's work to ensure it was readable for "non-experts".

From the narratives the paper identified four themes: *goal setting and planning; implementation, monitoring, and evaluation; the role of supervisors*, and *the impact of disciplines.* The first two highlight different ways that groups engaged in regulation during their projects. The latter two themes describe different factors that affected the groups' regulation.

The findings revealed the negative effect unfamiliarity can have on a group's ability to engage in successful regulation. The paper documented a form of CoRL which we coined "aggressive co-regulation" where a student attempts to forcefully co-regulate through a third party (in this case the supervisor). This highlighted how the supervisors can both help and hinder regulation through their interactions with groups and scaffolding of the course. Finally, the paper showed how one mode of regulation often triggered other modes; this was typically CoRL leading to SSRL.

4.4 Paper 4

Title: *Challenge Episodes and Coping Strategies in Undergraduate Engineering Research*

Universities are increasingly offering students an opportunity to engage in authentic research through UREs. Most studies on UREs focus on their outcomes such as their professional and personal benefits. However, few studies examine students' experiences and how they navigated through UREs. To address this knowledge gap in the literature this paper was driven by the following research questions:

RQ 1. *What challenges do students experience during UREs?*

RQ 2. *What coping strategies do students use in response to those challenges?*

A qualitative case study approach was taken with reflective writing collected from students taking part in UREs within Chalmers. The data was analysed using thematic analysis. Three themes were formed to represent the challenges the groups experienced: *organizing, planning and executing tasks; managing the group and its members;* and *receiving support from the teachers.* The coping strategies utilised by each group in response were outlined under the challenge that triggered them.

Groups were required to organise plan and manage their projects themselves which led to the challenges related to the first theme. For some groups this autonomy was new, and they had difficulty adapting to it. Others experienced challenges relating to the planning and executing of the work. Coping strategies for the challenges in this theme ranged from cooperative activities such as discussions, trial and error (when deciding what to do next), and having members take a leader role.

There were also challenges associated with managing the group and its members. Groups had to decide how they would work (e.g. together or separately), and deal with dependencies and knowledge gaps withing the groups. One group also had to contend with a troublesome and disruptive member. Coping strategies ranged from making use of internal experts (for tasks and knowledge gaps), to having group discussions, and sometimes just working as best as they could under the circumstances.

Teachers were seen as valuable sources of knowledge and were used as external sources of expertise and guidance. Challenges relating to the third theme include making contact with the relevant teacher (it was summer and during the covid pandemic), and ensuring groups received the “correct” or vital information. Coping strategies ranged from learning how to be specific with questions, developing communication strategies, or simply asking more questions.

From the findings we noted how challenges can have both positive and negative effects on the groups’ learning. Borrowing from the concept of desirable difficulties we labelled challenges that encourage learning as desirable. Conversely, challenges that had an adverse effect on learning were labelled undesirable. We encouraged designers of UREs to try and include desirable challenges while limiting instances of undesirable challenges. We also recommend that students taking part in UREs be provided some form of training to help them identify adequate coping strategies when confronted with challenges. Finally, an interesting observation from the data was the difference interdisciplinarity made in groups. Groups with a variety of disciplines were better suited to enacting coping strategies for challenges related to the second theme (managing the group and its members) compared to more homogenous groups. This was credited to their different experiences and areas of expertise which were especially useful when working on interdisciplinary project where members could take the role of an expert for certain tasks.

5. Discussion

In this chapter, I will discuss the contributions of the four papers of this thesis to both theory and practice related to the subject of this thesis – interdisciplinary project-based courses in engineering education. I will also outline some avenues for future research in that area.

The subject matter of this thesis contains many “moving parts” that are integrated with each other. With so many facets involved, there are therefore many potential ways of unravelling and discussing them. However, the common thread across all papers is the concept of interdisciplinarity, so I will begin as I did in chapter of the conceptual and theoretical framework by discussing interdisciplinarity in engineering education. I will then discuss my findings in relation to student groups in interdisciplinary PjBL, where I will discuss the themes of common ground, collaboration, and regulation of learning. I will conclude this discussion chapter with the teacher’s role in interdisciplinary PjBL. At this point I must restate that my goal for this thesis is not to gauge whether student groups achieved interdisciplinarity, nor will I try to measure the quality of the various groups’ learning. Instead, I will explore the various factors that affected the groups and the processes they used.

5.1 Interdisciplinarity in Engineering Education

I begin by reiterating my earlier observation that engineering education is increasingly incorporating interdisciplinarity in its programmes. And so, there needs to be a discussion, by both engineering education practitioners and researchers on what interdisciplinarity means within engineering education. **Paper 1** revealed that teachers of interdisciplinary courses in engineering education conceptualize the term “interdisciplinarity" in various ways. Whether knowingly or not, they touched on several disparate definitions that span numerous fields of study and theoretical debates. I found this rather surprising as I would have expected such a variety of conceptualizations from researchers who write about interdisciplinarity rather than practitioners. Additionally, individuals did not align exclusively with one definition. Instead, they often touched on more than one, even when those definitions would be considered epistemologically different. To untangle these conceptualizations, we developed two theoretical constructs: *epistemic interdisciplinarity* and *social interdisciplinarity.* These constructs can be used to frame different understandings of interdisciplinarity for both future research and engineering teachers’ training. Furthermore, we drew on Bal’s (2002) notion of a *travelling concept* to theorize the wide disparity between the teacher’s conceptualizations. By recognising interdisciplinarity as a travelling concept and by utilizing the concepts of epistemic and social interdisciplinarity, we provide a framework that allows for a better understanding of how the term can be understood and used.

The lack of a common or dominant definition of interdisciplinarity in engineering education was similarly identified in a recent study of engineering faculty and professionals by Ming et al. (2024). From **Paper 1**, which interviewed engineering teachers from three countries, I posit that universities are not dogmatically pushing one definition of interdisciplinarity. On one level this can be seen as a positive, with engineering teachers unbound by a single definition, allowing them to form their own interpretation of the term. However, a teacher's conceptualization of interdisciplinarity has an impact on how they design their courses (Feng et al., 2023). There might therefore be issues if a teaching team is tasked with designing and delivering a course, but they have vastly different understandings of what interdisciplinarity should be. Similarly, even with one teacher designing a course, the activities, group composition, or problems presented to the students might not be suitable for interdisciplinarity. The reliance of the course on a teacher's understanding of interdisciplinarity means that not all interdisciplinary courses are necessarily equivalent to each other in design or delivery. Similarly, Chen et al. (2021) observed that the widespread use of terms such as project- or problem- based courses can lead one to surmise that they are similar in design. However, Chen and colleagues found considerable variation in how such courses are designed and delivered. This leads me to draw two conclusions for us as engineering education researchers: first, we should exercise caution when discussing interdisciplinary PjBL, especially when comparing courses in engineering education with those from other fields of study. We need to consider how they are conceived and implemented by the teachers. Second, researchers would do well to continue researching and theorizing the concept of interdisciplinarity within engineering education. Researchers could, for instance continue to explore how the concept of interdisciplinarity travels (among engineering educators, professionals, and researchers) and what the basis is for the different conceptualizations. Such work would be a valuable contribution to pedagogical courses for teachers, helping teachers to negotiate and form an understanding of interdisciplinary education. It would complement the framework developed by Feng et al. (2023) that aims to aid teachers in designing multi-, inter-, and transdisciplinary courses. I was fortunate to be a part of a group of researchers that built upon this framework to develop a workshop for teachers to help guide them in their potential course design (Feng et al., 2024).

By theorizing interdisciplinarity within an engineering education context, we can question what the term means and how it occurs in practice. This process will also provide an opportunity to question how researchers view disciplines within engineering education. Additionally, as universities begin to incorporate outside perspectives into interdisciplinary project-based courses, there is a need to consider how this might influence our understanding of interdisciplinarity. **Paper 2** highlighted the challenge of framing such a situation. The paper focused on a Tracks course that had both full-time students and working professionals enrolled on it. While the course itself was designed to be interdisciplinary, the inclusion of professionals created a predicament. Typically, when non-academic actors are incorporated into such a course it is considered (Mode 2) transdisciplinary, with said actors taking on roles such as mentors or clients with no "stake" in the project's success. However, within this course the professionals took a student role which meant they could pass or fail the course. Of course, the professionals still brought their industry knowledge and networks with them to the course. The solution was the utilization of Repko and Szostak's (2017) concept of *interdisciplinarity plus,* which sits between interdisciplinarity and transdisciplinarity.

The interdisciplinarity plus approach is underutilized within engineering education but should be considered for project-based courses as the findings from **Paper 2** demonstrated how the inclusion of professionals proved to be a valuable experience for both them and the "regular" students. Such courses will also provide more opportunities to explore the concept of interdisciplinarity plus, which is similarly undertheorized within the literature. This will require a re-examining of how researchers interpret the disciplines of the courses' professional participants. The current default, to me, appears to only consider professional participants' discipline to be the one from their original university degrees. However, many of the professionals in **Paper 2** were no longer identified with the discipline their degrees were in (by both themselves and others) and were seen in terms of their careers instead. This leads to the question of how best to frame their disciplinary background when conducting research. This is important as a group with (for example) three members all from mechanical engineering might initially seem to be monodisciplinary, but one member might have spent 10 years working in a completely different field outside of that discipline.

Considering my earlier points on what constitutes a discipline, I feel they can be similarly applied to career roles. If we consider that a career role (for example an instructional designer) can have its own methods, procedures, knowledge, epistemology, and even culture then it follows that it could be considered equal to an academic discipline under the lens of interdisciplinary plus. Taking this further then, how would we begin to frame these career roles? The conceptions of interdisciplinarity from **Paper 1** provides two options for this. An epistemic interdisciplinarity perspective sees disciplines as distinct entities. This would consider the career role to be a disciplinary entity in its own right, with all of the aforementioned attributes listed previously. On the other hand, a social interdisciplinarity perspective is centred around individuals and the disciplinary knowledge and skills they bring to a group. This perspective would consider the professional's knowledge from their career to be on par with disciplinary knowledge.

5.2 Student Groups in Interdisciplinary PjBL

While the conceptualization of interdisciplinarity within engineering education is important, it only comprises one part of this thesis. **Papers 2, 3, and 4** are centred around students working in groups and so I now move the focus of this discussion section towards them. There are many aspects to consider when examining student groupwork in interdisciplinary PjBL and the effect the environment has on them. Selecting which ones to include here is not easy, but I have chosen to highlight three overarching dimensions that emerged from the papers: (1) finding "common ground", (2) collaboration in an interdisciplinary project-based environment, and (3) regulating learning in an interdisciplinary group.

5.2.1 Finding common ground

Summers and Volet (2010) point out how groupwork does not automatically result in collaborative learning. From an integrationist perspective, this can be applied to interdisciplinary education too. Groups with members from different disciplines working together on a project or problem will not automatically achieve an interdisciplinary “state” where they acquire interdisciplinary competencies. In this regard, finding common ground is essential if a group is to achieve interdisciplinarity (Repko, 2007). I would add to this by stating that common ground is similarly relevant to SoRL. The idea of SoRL requiring a common understanding of the problem or project that a group is working on is not unique (e.g. Miller & Hadwin, 2015). However, due to the few studies that have been conducted on SoRL in interdisciplinary groups, I believe the relevance of common ground has been overlooked by researchers of SoRL.

Students enrolled in the same degree programme in a European university will typically take the same, or almost the same, courses or modules. When a course in such a programme requires students to do group work, then it would be reasonable to surmise that the group members already share a common ground in terms of disciplinary knowledge. Such groups would therefore only need to achieve a common understanding of their problem and goal. While there is an overlap between common ground and common understanding, I do not believe they are the same thing. In an interdisciplinary context common ground includes the creation of a common language or a shared vocabulary (Repko, 2007). This is necessary as different disciplines can use the same words, but with very different meanings. However, differences in vocabulary are only one aspect which can cause difficulties for a group of students from different disciplines. Disciplines also come with their own cultures, procedures, and epistemological perspectives (Buanes & Jentoft, 2009; Wallin et al., 2017). The issues this creates was highlighted in **Paper 3** where we found that disciplinary differences (such as an approach to labwork) caused a failure to achieve SSRL and a negative socioemotional environment. Thus, we could show that a common understanding of a problem or task alone is not sufficient. Instead, we argue that effective SoRL requires a common understanding of the various methods and approaches employed by the different disciplines within a group.

An extension of this concept of common ground is the need for group members to form an understanding of each other and the project topic. This is addressed in **Paper 3,** which illustrates how a lack of familiarity of both subject matter and fellow group members inhibits SoRL. Conversely, an increase in knowledge of the topic and familiarity among members over time should lead to more effective SoRL. However, time alone is not the solution. **Paper 2** also demonstrated how unfamiliarity between group members can lead to a failure to co-regulate learning, despite time spent working on a project and increased knowledge of the project topic. Therefore, to account for an interdisciplinary setting, I would expand Miller and Hadwin’s (2015) instruction that group members need to be aware of each other’s abilities and learning goals to also include knowing each other as individuals. However, it could be argued that this should be necessary anyway for a positive socio-emotional environment. The issue of unfamiliarity and the challenges it causes can reverberate throughout groups’ attempts to engage in interdisciplinary PjBL. It has a particular effect on a group’s regulation of learning and so I will revisit the matter again in that subsection.

5.2.2 Collaboration in an interdisciplinary project-based environment

PjBL requires the students to plan, design, implement, and evaluate their solution to a complex or authentic problem (Frank & Barzilai, 2004; Ríos et al., 2010). Groups taking part in PjBL are therefore given significant agency in the running of their projects. The amount of agency given to groups can vary considerably depending on the course and the "level" of the students. For example, the URE projects in **Paper 4** differed from the project-based courses in **Papers 2 and 3**, as they were unstructured with no common classes, and groups were expected to plan and run all aspects of the project themselves. By comparing all three papers we can see how the unstructured nature of the UREs combined with increased agency (when students are unused to it) can cause significant struggle for groups in the initial stages of a project. These struggles were absent in **Papers 2 and 3** in project-based courses that provided structure, with an expectation that groups would plan and manage their projects. While there were minor differences in the various course structures (including project requirements and teacher support), I believe these combined with the students' higher level of learning are the reason the students experienced less challenges and issues related to their agency. This might therefore be a solution that gives student groups agency but reduces anxiety and stress allowing for a better socioemotional environment within the group.

However, I must also point out that uncertainty and struggle do not necessarily result in a negative outcome for learning. **Paper 4** introduces the concept of desirable challenges, which borrows from Bjork and Bjork's (2011) desirable difficulties. With the correct support from teachers, this unstructured approach can lead to desirable challenges (which stimulate learning) and reduce instances of undesirable challenges (which inhibit learning). Similarly, teachers can help groups with the coping strategies they choose in response to challenges. Groups should be guided or encouraged to use desirable strategies, which enable learning, over undesirable strategies, which don't (e.g. refusing to work until they receive more instructions). I therefore posit that the increase in agency (and reduced structure) requires some training for students that are not used to it, with similar forms of structure and support provided depending on the student's experiences and learning levels.

Another contribution of this thesis is the insight it provides into how student groups manage and organise their work. **Papers 2 and 3** highlight the challenge interdisciplinary student groups face of scheduling work and meetings when group members have different schedules. This challenge was further complicated by the introduction of professionals in **Paper 2**. A popular solution to this challenge is to divide work among group members. This does not necessarily mean working individually on tasks, but rather not working together as a whole group. This method of working (splitting tasks) has both advantages and disadvantages. The main advantage is efficiency, which is naturally why various groups employed this method. Splitting tasks also provides an opportunity for students to work on tasks related to their disciplines (when possible). Unfortunately, splitting up work can also result in students working alone on tasks that are outside of their discipline if there is no expert in the group. While it may be effective in terms of efficiency, distributing tasks among a group comes at the expense of learning. According to Summers and Volet (2010), and highlighted in Figure 1, working independently will result in poorer learning in terms of knowledge acquisition. When a group splits up tasks, the attainment of knowledge outside of one's tasks is dependent on knowledge sharing (typically in meetings) and active monitoring of each other's work. While students did report they learnt of the various aspects of their projects to some level, they would have gained deeper learning had they worked together on tasks. Relying on meetings to co-construct knowledge is a risky strategy in terms of learning as Summers and Volet (2010) found some groups were not likely to spend a significant amount of time discussing content during meetings.

The danger then lies in the focus students put on the completion of the project and the satisfaction they gain from it. Unfortunately, satisfaction from the completion of a project does not mean students have engaged in productive collaborative learning (Volet et al., 2009). This is not to downplay the importance of satisfaction with a project, and it comes with an added dimension in an interdisciplinary setting. MacLeod and van der Veen (2020) noted how students' satisfaction relied on their disciplinary skills or knowledge being needed by their group to perform necessary tasks. These tasks need to be neither too simple nor too complex. Similarly, their tasks need to be close to what they perceive their discipline to be and doable based on what they had learned from their home disciplines (MacLeod & van der Veen, 2020). Students working on tasks suited to their discipline may lead to deeper learning for them and a strengthening of their disciplinary identity. However, working individually on said tasks can deprive other group members from learning more of that discipline. To put this in terms of the competencies to be gained from interdisciplinary work according to **Paper 1**: one student will achieve the "learning more about your own discipline" competency while the other group members will not gain as much of the "gaining knowledge of or from other disciplines" competency.

There are two potential issues teachers need to consider when student groups elect to split the work up among themselves. First, students might not be aware of how important the co-construction of knowledge is to collaborative learning. Its importance should therefore be impressed upon student groups taking part in PjBL. Secondly, students need to be encouraged to look beyond the completion of projects and engage in learning. This can be quite difficult as students can be pre-occupied with completing their courses and achieving high grades. Furthermore, even when groups recognise the value of knowledge co-construction (and other collaborative learning processes) they might still not engage in it if they don't feel it is relevant or needed to complete their project (Summers & Volet, 2010). Preparing students to solve complex or wicked problems is often cited as a raison d'être of interdisciplinary PjBL and initiatives such as Tracks. Students can therefore be forgiven for believing the goal of project-based courses is to simply solve such problems. Instead, teachers need to get students to recognize that project-based courses are an opportunity for them to *learn* how to approach, work on, and ultimately solve these problems. One possible solution is the approach taken by the course in **Paper 2**, where the projects were focused on presenting knowledge to the class. All the interviewee's stated their goal with the project and course was to learn rather than simply passing, and the projects were seen as an opportunity to learn more about a given aspect of battery technology. However, these projects did not require the groups to design or create an object, nor were the groups expected to solve a specific complex problem. Perhaps a solution lies between the two. In addition to their product or solution, students could also present what they learned from the project or be required to teach the class about the subject using their project or solution.

5.2.3 Regulating learning in an interdisciplinary group

Examining SoRL in interdisciplinary groups over the course of a project resulted in some interesting findings. Some of these findings are supported by previous studies that were performed on monodisciplinary groups, usually taking part in what could be labelled problem-based learning. Other findings expand on SoRL theory by demonstrating the effects an interdisciplinary PjBL environment had on groups and their regulation. There are potentially numerous ways to discuss the findings of the papers in relation to SoRL. I have chosen to highlight *goal setting and planning* as it was one of the most prominent themes across **Papers 2, 3, and 4**. I will also discuss *regulation in a PjBL environment*.

Goal Setting and Planning

Goals are the lynchpin for the regulation of learning. The regulation processes of planning, monitoring, and evaluation are all set against the individual's or group's goals (Hadwin et al., 2017; Zimmerman, 2000). However, within the context of interdisciplinary PjBL, setting group goals has proven to be no easy task. As I mentioned previously, PjBL requires groups to set their own project goals and objectives. This increased agency coupled with an interdisciplinary project-based environment raises three issues I wish to highlight. These three issues are sometimes intertwined with each other, which only compounds the challenges they present.

The first issue is the unstructured and open nature of the environment, which can mean few detailed requirements are provided for projects. **Paper 4** reveals how such an environment can be particularly challenging when those that are unused to it are asked to form project goals and plans. Though the courses in **Papers 2 and 3** were more structured, the papers reveal how this environment also creates some uncertainty at the initial stages of a project.

The second issue is a lack of familiarity with the subject matter or project topic. The level of unfamiliarity can vary depending on the course and the disciplinary backgrounds of the group members. As I mentioned previously, the aim of interdisciplinary project-based courses is to have student groups work on complex problems which require input from more than one discipline. Ideally, each group would have the disciplinary knowledge required for their project. Unfortunately, group composition is dependent on course enrolment, which does not always guarantee an ideal number of students from each discipline. A course might therefore have a monodisciplinary group or perhaps a group is missing someone with relevant disciplinary knowledge. **Paper 3** highlights how difficult it can be to form a goal and plan when one is unfamiliar with the subject matter.

Finally, there is the issue of group members being unfamiliar with each other, which is an extension of the theme of common ground I discussed earlier. There is a likely chance that groups composed of students from the same degree programme will already know each other and have probably worked together previously. However, in interdisciplinary project-based courses this is considerably less likely as students can come from a variety of different degree programs. The negative impact this unfamiliarity can have at the goal setting and planning stage of a project is discussed in **Paper 3,** where it was seen to prevent the formation of a plan and SSRL.

These three issues contributed to two common problems for setting goals: choosing an adequate level of difficulty and achieving SSRL. Choosing the correct level of difficulty can itself be challenging with the three issues I outlined above. Afterall, it is hard to gauge the correct level of difficulty for a goal when a group is unfamiliar with the topic and each other. This is addressed in **Paper 3,** which illustrates how the combination of these forms of unfamiliarity can lead to a lack of consensus (primarily over choosing an adequate level of difficulty) when forming a goal and thus a failure to achieve SSRL. The paper also underscores how much of a challenge it is to choose the correct level of difficulty, even when familiar with the subject matter. **Paper 3** highlights how capable groups can underestimate themselves and later regret the level of difficulty they chose (that it could have been more difficult). From a regulation standpoint, the level of difficulty is important as Iiskala et al. (2011) found a correlation between a task's difficulty and an increase in SoRL (specifically socially shared metacognitive regulation). So, it stands to reason that a goal with an adequate level of difficulty should similarly spur SoRL. As SSRL is the process of a group regulating itself, the formation of a group goal is essential and requires consensus, which in turn often needs negotiation (Hadwin et al., 2017; Miller & Hadwin, 2015). However, the issues outlined above – lack of requirements or details, unfamiliarity with the topic and fellow group members – all make achieving SSRL more difficult in these initial stages of a project.

Regulation in a PjBL environment

There are two additional insights from the papers that I wish to highlight due to their contribution to the literature on regulation of learning. These are group monitoring strategies over the course of an interdisciplinary project, and the concept of "aggressive" CoRL.

Monitoring plays an important function in relation to regulation and collaborative learning. Groups and individuals need to monitor their learning, and the progress and quality of their work against their goals (Miller & Hadwin, 2015). **Paper 3** draws attention to how the appearance of effective monitoring and regulation over the course of a project can prove deceptive. There is a potential danger that progress becomes detached from the original goals, leading to a compartmentalization of regulatory processes, where planning monitoring and evaluation become transfixed on weekly progress (e.g. from meeting to meeting). This leads to the appearance of effective monitoring, but results in an unintentional divergence from the original goals. This not to say all the regulatory processes in such a group are ineffective: such groups can otherwise engage in quite effective episodes of CoRL and SSRL. According to Rogat and Linnenbrink-Garcia (2011), this disconnection from the group goals would count as low-quality monitoring, which I would agree with. However, I feel it reflects the complicated nature of regulation within a group project that is held over several weeks. It is an example of how otherwise competent groups of advanced learners can still make fundamental mistakes. My recommendation for practice is that groups of all levels and experience require some form of scaffolding or training to aid them in processes that will enable collaborative learning and high-quality monitoring. Groups can monitor their progress and the quality of their work against the goals and plans they set themselves, but how do they monitor their learning over the course of a project? Earlier (Section 5.2.2), I discussed how groups tended to split their work into tasks, which are then distributed among the group. In such cases, group meetings are typically where groups can engage in monitoring of learning. However, this presents a challenge as it limits monitoring to small windows. This challenge is addressed in **Papers 2 and 3,** where effective solutions included continuous communication, monitoring of shared documents, and periodically checking in on group members. I consider these to be "dynamic" monitoring as it is more continuous than only engaging in monitoring during meetings (which would be static by comparison). Dynamic monitoring activities might require more time and commitment from students and groups that are probably already "time poor" due to course commitments. Nevertheless, dynamic monitoring activities should be encouraged as they allow for more timely interventions (in the form of CoRL) and opportunities for learning.

The second insight comes from **Paper 3,** which introduces the concept of "aggressive" CoRL, a form of co-regulation that we (the authors) had not previously seen in the literature. Aggressive CoRL occurs when an individual (or individuals) attempts to co-regulate a group through a teacher or supervisor. This is done by individually approaching the teacher and convincing them that a certain method or plan is best for the group, then having the teacher co-regulate the group accordingly. It relies on the group's perception of the teacher as an authoritative figure and the teacher's willingness to engage in external CoRL. Attempts to dominate a group using CoRL have been reported previously (e.g. Grau & Whitebread, 2012), but those cases only involved one group member trying to control others in the group directly. To adequately label this "weaponization" of the teacher and the regulation process, we coined the phrase "aggressive" CoRL. I must stress that aggressive CoRL should not be conflated with all episodes of external CoRL that are initiated by students or the group, only those where external CoRL is used to dominate the group. The use of aggressive CoRL is very detrimental. It can lead to a cycle of repeated episodes of aggressive CoRL and a negative socioemotional environment. This then becomes detrimental to the learning process as a negative socioemotional environment will lead to less successful episodes of SoRL and a breakdown of group cohesion (Rogat & Linnenbrink-Garcia, 2011).

The question then for teachers is how to prevent or reduce instances of aggressive CoRL, without abandoning external CoRL. The findings from **Paper 3** indicate that episodes of aggressive CoRL are likely to decrease in number over the course of the project as the group becomes more familiar with each other (on a working and personal level) and the project subject matter. I would therefore recommend teachers to encourage groups to get to know one another. Groups should also be told what a positive socioemotional environment is, how it benefits collaborative learning, and the types of interactions that can encourage it. Positive socioemotional interactions include valuing and seeking each other's opinions, recognizing members' contributions, including group members (e.g. in meetings and decisions), being attentive, and engaging in actions that support group cohesion (Bakhtiar & Hadwin, 2020; Rogat & Linnenbrink-Garcia, 2011).

5.3 The Teachers' role in interdisciplinary PjBL

While my research has primarily focused on students in groups taking part in interdisciplinary PjBL, the role and influence of teachers cannot be ignored. As teachers are typically responsible for the design and delivery of interdisciplinary project-based courses, they have a significant impact on whether student groups successfully engage in collaborative learning and gain interdisciplinary competencies.

Paper 3 and 4 highlighted how teachers are identified as valuable sources of knowledge and as authoritative figures. A common form of contact is though weekly meetings, with extra contact on occasion for advice or additional information. Limited (or no contact) with teachers was shown by **Paper 4** to result in significant problems, such as struggling with tasks and dissatisfaction. In terms of SoRL, we can label the teacher-group interactions as external co-regulation, as the students learning is being regulated from outside the group. **Paper 3** illustrated how this external CoRL can lead to further regulation as groups engage in SSRL among themselves afterwards.

This external CoRL, unfortunately, did not always have a positive effect on the groups' learning. **Paper 4** addressed the issue of instructions being considered unclear, too few, late, or conflicting with other instructions or answers. Teachers can also have a directly negative impact on regulation, as **Paper 3** highlights how the external co-regulation of a group can inadvertently disrupt their learning and cause a (temporary) break down in their ability to engage in SSRL. This, to me, is slightly unusual. While previous literature has shown examples of CoRL hindering learning (e.g. Rogat & Adams-Wiggins 2015), they involved group members as the disruptive regulators, not teachers. Indeed, the effects teachers can have on a group via CoRL appears to be under researched, which is surprising considering the value placed on their knowledge by student groups. To avoid negative instances of external CoRL I would urge those supervising groups to be cautious in how they express their ideas and advice. Despite the age and advanced level of the students in project-based courses in university, teachers are still seen as authoritative figures, whose opinion carries weight (hence the use of aggressive CoRL). Teachers should therefore avoid "directive" co-regulation, where groups are asked or told to do something without considering their opinions, and instead engage in “facilitative” co-regulation, which considers the groups well-being and aims encourage high-quality learning (Rogat & Adams-Wiggins, 2015).

Based upon the findings from **Papers 2, 3 and 4,** I posit that a key contributor to a group’s success is scaffolding. Concerningly, Kjellberg et al. (2023) found that, while Tracks teachers put a lot of effort on the development of content knowledge for their courses, they put little thought into how to scaffold their courses to encourage collaboration. The benefits of scaffolding are highlighted in **Paper 3,** where it was shown to aid in the monitoring and evaluation of work. But what might this scaffolding look like? Groups should be encouraged in the planning phase to set out a concrete plan and encouraged to regularly monitor and evaluate their work against their goal and plan. Regular supervision meetings should be held to provide valuable and consistent contact between the teachers and groups. These meetings provide teachers with an opportunity to support the groups learning and regulation. For example, prompts can be used to remind students of processes such as monitoring and evaluation, to encourage regulation of the group, and to connect tasks with learning (Quackenbush & Bol, 2020).

From an interdisciplinary perspective, MacLeod and van der Veen (2020) recommend regular supervision meetings so that groups can be steered if necessary to ensure they do not work on the project in a monodisciplinary (and I would add multidisciplinary) way. When supervising interdisciplinary groups, teachers should also be aware of the potential differences between students’ disciplinary knowledge and procedures. This applies equally to broad and narrow interdisciplinary groups. It would be incorrect to assume that all engineering students share the same procedures and vocabulary, as highlighted in **Paper 3,** where different disciplines can have very different expectations in terms procedures and work. Teachers should therefore make students aware that there could be differences between their disciplines that are not immediately apparent or obvious. Additionally, students should be encouraged to meet and become familiar with each other and each other’s disciplines. This should help develop a common understanding of each other and will help them engage in better SoRL.

Of course, not all courses and student cohorts are the same in terms of the support they require for project work and for SoRL in general. An example being the groups in **Paper 2**, none of whom required any help or support from the course teachers outside of clarifying if their project goal was passable. I credit this to the structure and nature of the project and its requirements. I therefore echo Sulla et al.’s (2023) point that teachers need to adapt their support strategies and project/course design according to the level and abilities of their students.

6. Conclusion

The proliferation of interdisciplinary project-based courses offered to engineering students has created a need for research into this environment and its effect on learning processes. This is especially relevant for SoRL, as its theories have been primarily formed based on monodisciplinary groups. This thesis addressed this research gap through four papers, each of which examined different aspects of regulation, learning, and theory in an interdisciplinary project-based environment. In this final chapter I will provide a summary of this thesis' findings and how they contribute to theory. I will also address the limitations of this thesis and present recommendations for future research.

When analysing engineering teachers' conceptualizations of interdisciplinarity, we found it to be a *travelling concept*. That is to say, interdisciplinarity is a concept that takes on different meanings as it metaphorically travels between fields of study or between scholars. This thesis outlines two overarching understandings of interdisciplinarity in engineering education: *epistemic* interdisciplinarity and *social* interdisciplinarity. The former considers interdisciplinarity to be the interaction and joining of knowledge from different disciplines, while the latter considers it to be the interaction and joining of knowledge between people from different disciplines. This empirically grounded theorization of interdisciplinarity provides a framework for articulating and negotiating understandings of interdisciplinarity within engineering education and therefore it has practical value as well.

Drawing on the notion of *interdisciplinarity plus,* this thesis suggests a conceptualization of educational settings that incorporate non-academic actors (here professionals) into project-based courses as co-learners. The inclusion of engineering professionals as co-learners with engineering master's students led to learning benefits and was seen favourably by both cohorts. However, a group's composition – student only, professionals only, or a mix of both – was found to have an impact on their epistemic practices. The thesis proposes a new way of considering interdisciplinarity and how professionals can be incorporated into what is an otherwise academic framework that does not account for career experiences.

This thesis also has two findings that help to expand existing theories of SoRL. The first contribution is a form of regulation that we labelled "aggressive" CoRL. This form of CoRL differs from other examples of negative or unproductive forms of co-regulation as a person in a perceived position of power (a teacher) is used by one member to force their regulation on others. I posit that this form of CoRL has not been previously documented as there are few studies of SoRL that examine regulation over a project.

The second contribution to the theories of SoRL is the impact unfamiliarity can have on a group's ability to regulate themselves. Groups taking part in interdisciplinary project-based courses can find their attempts to regulate learning thwarted due to a lack of familiarity with each other, the different disciplines involved, and the subject matter. I propose that one way to help alleviate this issue in interdisciplinary PjBL is to utilize the concept of *common ground* from interdisciplinary theory. The development of common ground and understanding will help bridge the gap between disciplinary knowledge and procedures, while also giving insight into how group members think and approach problems.

Finally, this thesis makes two contributions in terms of methodology in relation to SoRL. The first is concerned with documenting instances of SoRL, which remains a challenge for studies on regulation of learning. This thesis contributes to solving this challenge by experimenting with narratives as a means to document a group's SoRL over the course of a project. Our use of narratives allowed us to present episodes of SoRL as the project unfolded, showing how it was shaped by different events and choices made by the groups. It is a method that should be explored further as we need to learn more about how groups engage in SoRL over time in authentic project environments, rather than focusing on groups brought together to solve a task.

The second contribution to methodology lies in our use of SoRL to identify a group's epistemic practices when taking part in a project-based course. The method also allowed us to identify and expand on previous findings relating to SoRL. I believe there is great potential in the use of SoRL as an analytical tool to identify collaborative learning, epistemic practices, and a way to study groupwork. As the study of SoRL progresses, this use of its theories demonstrates how they can be expanded on and utilized in different ways.

There are, however, some limitations to this thesis and the papers it is built on. The first is that all of the data is qualitative in nature, which is dependent on the authors' interpretation of it. To ensure credibility during data analysis, the co-authors not working on the analysis would check the interpretations and various iterations of coding against the original data. When more than one author worked on data analysis, regular meetings were held to discuss and compare codes. The final results and interpretations were also checked against the literature where applicable to ensure confirmability. Another potential limitation is the use of interviews, which were held after the participants had completed their courses. They were therefore dependent on the interviewee's recollection and ability to express themselves. Similarly, when recounting actions or episodes of regulation, some steps or processes might have been left out, which would have shown more examples of movement between different forms of regulation. For example, an episode described as "we discussed it and decided" indicates SSRL, but there may have been some small instances of CoRL within the episode. For future studies into the topics of collaborative learning and SoRL, I recommend using a wider range of data collection methods. However, if one were to only use interviews, I would recommend multiple points of data collection throughout the project. In terms of the data collection itself, I should note that all interviews and reflective writing were done through the medium of English. While English is my first language, it was a secondary language for most (if not all) of the participants in the four papers. This might have had an effect on how they expressed themselves. However, those studying at master's level or higher, work predominantly through English in their courses, with many of those interviewed coming from outside Sweden. All those I interviewed appeared comfortable with using English for communication. Finally, we were unable to interview all members of the groups that featured in the third paper. Had we been able to interview them, then they could have contributed to more detailed narratives for each group. For future studies wishing to use the narrative structure I recommend either interviewing all group members individually or holding a mix of focus group and individual interviews.

This leads me to my recommendations for future research. From my reading of the literature, researchers are still experimenting with ways to study and support SoRL. This, coupled with the low number of SoRL studies on groups taking part in interdisciplinary projects, highlights a significant research gap. One avenue of research is to deliver a “pre-project” class to select groups to explain the principles of regulation, its benefits to learning, and how it could look through examples. Then throughout the project deliver reminders or prompts to the groups through the teachers or group supervisors. Their ability to regulate throughout the project can then be compared with control groups to ascertain if there was an improvement in their ability to engage in SoRL. Data could be collected using a spectrum of methods, including interviews and questionnaires, collected throughout the project. There is also the possibility of conducting a similar study, but with the use of AI. Järvelä et al. (2023) have proposed that AI could be used to help analyse large quantities of data to find episodes of SoRL. This would allow for the collection of data that might be simply unwieldly for human researchers, e.g. video recordings of all group meetings, chat logs, emails, and logs of changes to documents. There is also the possibility of using AI to prompt and support SoRL (Järvelä et al., 2023). A recent study by Molenaar (2022) has demonstrated a successful AI prototype that helps individual students develop their ability to self-regulate their learning. It should therefore be possible to develop an AI tool that would similarly help strengthen a group’s ability to engage in SoRL.

I will conclude this thesis by encouraging others to continue to explore the unique environment that interdisciplinary project-based courses provide. There are numerous avenues that such research can take, using either the theoretical framework underpinning this thesis or others. I mentioned in the introduction how my initial readings in relation to these courses piqued my interest in the subject. Five years and one thesis later, I am still keen to conduct more research on its various aspects and have become a supporter of such courses.

References

Adams, P. (2006). Exploring social constructivism: Theories and practicalities. *Education 3-13*, *34*(3), 243–257. https://doi.org/10.1080/03004270600898893

Alshamrani, A., & Bahattab, A. (2015). A comparison between three SDLC models waterfall model, spiral model, and Incremental/Iterative model. *International Journal of Computer Science Issues (IJCSI)*, *12*(1), 106.

Alshenqeeti, H. (2014). Interviewing as a Data Collection Method: A Critical Review. *English Linguistics Research*, *3*(1), Article 1. https://doi.org/10.5430/elr.v3n1p39

Ameri, M. (2020). Criticism of the sociocultural theory. *Budapest International Research and Critics Institute-Journal (BIRCI-Journal) Volume*, *3*, 1530–1540.

Arthars, N., Markauskaite, L., & Goodyear, P. (2024). Constructing shared understanding of complex interdisciplinary problems: Epistemic games in interdisciplinary teamwork. *Journal of the Learning Sciences*, *33*(2), 405–442. https://doi.org/10.1080/10508406.2024.2341390

Bakhtiar, A., & Hadwin, A. F. (2020). Dynamic interplay between modes of regulation during motivationally challenging episodes in collaboration. *Frontline Learning Research*, *8*(2), 1–34. Scopus. https://doi.org/10.14786/flr.v8i2.561

Bal, M. (2002). *Travelling Concepts in the Humanities: A Rough Guide*. University of Toronto Press.

Barana, A., Boetti, G., Marchisio, M., Perrotta, A., & Sacchet, M. (2023). Investigating the Knowledge Co-Construction Process in Homogeneous Ability Groups during Computational Lab Activities in Financial Mathematics. *Sustainability*, *15*(18). https://doi.org/10.3390/su151813466

Beers, P. J., Boshuizen, H. P. A. (Els), Kirschner, P. A., & Gijselaers, W. H. (2005). Computer support for knowledge construction in collaborative learning environments. *Learning in Innovative Learning Environments*, *21*(4), 623–643. https://doi.org/10.1016/j.chb.2004.10.036

Bernhard, J., & Baillie, C. (2016). Standards for Quality of Research in Engineering Education. *International Journal of Engineering Education*, *32*(6), 2378–2394.

Bernini, M., & Woods, A. (2014). Interdisciplinarity as cognitive integration: Auditory verbal hallucinations as a case study. *WIREs Cognitive Science*, *5*(5), 603–612. https://doi.org/10.1002/wcs.1305

Bjork, E. L., & Bjork, R. A. (2011). Making things hard on yourself, but in a good way: Creating desirable difficulties to enhance learning. *Psychology and the Real World: Essays Illustrating Fundamental Contributions to Society*, *2*(59–68).

Boden, M. A. (1999). What is interdisciplinarity. *Interdisciplinarity and the Organization of Knowledge in Europe*, 13–24.

Bogdanovs, A., Bubovich, A., & Galkin, I. (2022). Interdisciplinary Project-based Learning Approach Implementation for Undergraduate Electrical Engineering Students. *2022 IEEE 63th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)*, 1–7. https://doi.org/10.1109/RTUCON56726.2022.9978862

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Brinkmann, S., & Kvale, S. (2015). *Interviews: Learning the craft of qualitative research interviewing.* (3rd ed.). Sage publications.

Brundiers, K., Wiek, A., & Redman, C. L. (2010). Real-world learning opportunities in sustainability: From classroom into the real world. *International Journal of Sustainability in Higher Education*, *11*(4), 308–324. https://doi.org/10.1108/14676371011077540

Buanes, A., & Jentoft, S. (2009). Building bridges: Institutional perspectives on interdisciplinarity. *Futures*, *41*(7), 446–454. https://doi.org/10.1016/j.futures.2009.01.010

Cartrette, D. P., & Melroe-Lehrman, B. M. (2012). Describing Changes in Undergraduate Students' Preconceptions of Research Activities. *Research in Science Education*, *42*(6), 1073–1100. https://doi.org/10.1007/s11165-011-9235-4

Cassell, C., Cunliffe, A., Grandy, G., & Simpson, B. (2018). Pragmatism: A Philosophy of Practice. In pages 54-68 & pages 54-68, *The SAGE Handbook of Qualitative Business and Management Research Methods: History and Traditions*.

Chen, J., Kolmos, A., & Du, X. (2021). Forms of implementation and challenges of PBL in engineering education: A review of literature. *European Journal of Engineering Education*, *46*(1), 90–115. https://doi.org/10.1080/03043797.2020.1718615

Clarke, V., & Braun, V. (2014). Thematic analysis. In *Encyclopedia of critical psychology* (pp. 1947–1952). Springer.

Cobb, P. (1994). Where is the mind? Constructivist and sociocultural perspectives on mathematical development. *Educational Researcher*, *23*(7), 13–20.

Cohen, L., Manion, L., & Morrison, K. (2011). *Research methods in education.* (Depending on RTAC solution; 7. ed.). Routledge; Chalmers Library Print Collection. https://search.ebscohost.com/login.aspx?direct=true&db=cat07470a&AN=clc.fbeb9040.bee0.4cdb.9172.c8ff6625e93a&site=eds-live&scope=site&authtype=guest&custid=s3911979&groupid=main&profile=eds

Crawley, E. F. (2018). Reimagining Engineering Education. *Mechanical Engineering*, *140*(7), 16–16.

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative, and mixed methods approaches / John W. Creswell, PhD, Department of Family Medicine, University of Michigan, and J. David Creswell, PhD, Department of Psychology, Carnegie Mellon University.*

(clpc.oai.edge.chalmers.folio.ebsco.com.fs00001000.9441ac82.449b.4963.9334.fae3194d5896; Fifth edition.). SAGE; Chalmers Library Print Collection. https://research.ebsco.com/linkprocessor/plink?id=020ee014-b1fe-3de1-84aa-1bb7b7a37f32

Creswell, J. W., & Guetterman, T. C. (2021). *Educational research: Planning, conducting and evaluating quantitative and qualitative research.* (Depending on RTAC solution; 6th ed., global edition.). Pearson; Chalmers Library Print Collection. https://search.ebscohost.com/login.aspx?direct=true&db=cat07470a&AN=clc.b4a9c92f.89d2.4fc9.ac3d.179847085900&site=eds-live&scope=site&authtype=guest&custid=s3911979&groupid=main&profile=eds

Crotty, M. (1998). *The Foundations of Social Research: Meaning and Perspective in the Research Process*. SAGE.

De Hei, M. S. A., Strijbos, J.-W., Sjoer, E., & Admiraal, W. (2015). Collaborative learning in higher education: Lecturers' practices and beliefs. *Research Papers in Education*, *30*(2), 232–247. https://doi.org/10.1080/02671522.2014.908407

de Villiers, C., Farooq, M. B., & Molinari, M. (2022). Qualitative research interviews using online video technology – challenges and opportunities. *Meditari Accountancy Research*, *30*(6), 1764–1782. https://doi.org/10.1108/MEDAR-03-2021-1252

DiDonato, N. C. (2013). Effective self- and co-regulation in collaborative learning groups: An analysis of how students regulate problem solving of authentic interdisciplinary tasks. *Instructional Science*, *41*(1), 25–47. https://doi.org/10.1007/s11251-012-9206-9

Dillenbourg, P. (1999). *What do you mean by collaborative learning?*

Doody, O., & Noonan, M. (2013). Preparing and conducting interviews to collect data. *Nurse Researcher*, *20*(5).

Enelund, M., & Briggs, K. H. (2020). *Tracks for change, flexibility, interdisciplinarity and creativity in engineering education*. *1*, 37.

English, L. D. (2016). STEM education K-12: Perspectives on integration. *International Journal of STEM Education*, *3*(1), 3. https://doi.org/10.1186/s40594-016-0036-1

Feng, X., Ylirisku, S., Kähkönen, E., Niemi, H., & Hölttä-Otto, K. (2023). Multidisciplinary education through faculty members' conceptualisations of and experiences in engineering education. *European Journal of Engineering Education*, *48*(4), 707–723. https://doi.org/10.1080/03043797.2023.2185126

Fiore, S. M. (2008). Interdisciplinarity as Teamwork: How the Science of Teams Can Inform Team Science. *Small Group Research*, *39*(3), 251–277. https://doi.org/10.1177/1046496408317797

Flynn, S. I. (2023). Culture and Conformity. In *Salem Press Encyclopedia* (89185409). Great Neck Publishing; Research Starters. https://research.ebsco.com/linkprocessor/plink?id=b54c70c8-4270-3cc4-b344-fc637e40c234

Frank, M., & Barzilai, A. (2004). Integrating alternative assessment in a project-based learning course for pre-service science and technology teachers. *Assessment & Evaluation in Higher Education*, *29*(1), 41–61. https://doi.org/10.1080/0260293042000160401

Garcia, R., & Gracias, N. (2012). Project-based learning as a motivating tool to teach computer vision. *Proceedings of the 2012 IEEE Global Engineering Education Conference (EDUCON)*, 1–5. https://doi.org/10.1109/EDUCON.2012.6201174

Gentile, J., Brenner, K., & Stephens, A. (2017). *Undergraduate research experiences for STEM students: Successes, challenges, and opportunities* (p. 258). Scopus. https://doi.org/10.17226/24622

Grau, V., & Whitebread, D. (2012). Self and social regulation of learning during collaborative activities in the classroom: The interplay of individual and group cognition. *Learning and Instruction*, *22*(6), 401–412. https://doi.org/10.1016/j.learninstruc.2012.03.003

Greisel, M., Melzner, N., Kollar, I., & Dresel, M. (2023). How are achievement goals associated with self-, co-, and socially shared regulation in collaborative learning? *Educational Psychology*, *43*(4), 384–402. https://doi.org/10.1080/01443410.2023.2211751

Guardiola, I.G., Dagli, C., & Corns, S. (2013). Using University-Funded Research Projects to Teach System Design Processes and Tools. *IEEE Transactions on Education*, *56*(4), 377–384. https://doi.org/10.1109/TE.2013.2240388

Hadgraft, R. G., & Kolmos, A. (2020). Emerging learning environments in engineering education. *Australasian Journal of Engineering Education*, *25*(1), 3–16. https://doi.org/10.1080/22054952.2020.1713522

Hadwin, A. F., Järvelä, S., & Miller, M. (2017). Self-Regulation, Co-Regulation, and Shared Regulation in Collaborative Learning Environments. In *Handbook of Self-Regulation of Learning and Performance* (pp. 83–106). Routledge. https://doi.org/10.4324/9781315697048-6

Hadwin, A. F., & Oshige, M. (2011). *Self-Regulation, Coregulation, and Socially Shared Regulation: Exploring Perspectives of Social in Self-Regulated Learning Theory.* Undefined. /paper/Self-Regulation%2C-Coregulation%2C-and-Socially-Shared-Hadwin-Oshige/4011795f863481799a52c4ea92209fba304de99f

Hoover, L. A. (1994). Reflective writing as a window on preservice teachers' thought processes. *Teaching and Teacher Education*, *10*(1), 83–93. https://doi.org/10.1016/0742-051X(94)90042-6

Hsu, R.C., & Liu, W.C. (2005). Project based learning as a pedagogical tool for embedded system education. *ITRE 2005. 3rd International Conference on Information Technology: Research and Education, 2005.*, 362–366. https://doi.org/10.1109/ITRE.2005.1503143

Iiskala, T., Vauras, M., Lehtinen, E., & Salonen, P. (2011). Socially shared metacognition of dyads of pupils in collaborative mathematical problem-solving processes. *Learning and Instruction*, *21*(3), 379–393. https://doi.org/10.1016/j.learninstruc.2010.05.002

Iiskala, T., Volet, S., Lehtinen, E., & Vauras, M. (2015). Socially Shared Metacognitive Regulation in Asynchronous CSCL in Science: Functions, Evolution and Participation. *Frontline Learning Research*, *3*(1), Article 1. https://doi.org/10.14786/flr.v3i1.159

Issa, H. B., & Khataibeh, A. (2021). The Effect of Using Project Based Learning on Improving the Critical Thinking among Upper Basic Students from Teachers' Perspectives. *Pegem Journal of Education and Instruction*, *11*(2), 52–57.

Ivanitskaya, L., Clark, D., Montgomery, G., & Primeau, R. (2002). Interdisciplinary learning: Process and outcomes. *Innovative Higher Education*, *27*, 95–111.

Järvelä, S., & Hadwin, A. F. (2013). New Frontiers: Regulating Learning in CSCL. *Educational Psychologist*, *48*(1), 25–39. https://doi.org/10.1080/00461520.2012.748006

Järvelä, S., Nguyen, A., & Hadwin, A. (2023). Human and artificial intelligence collaboration for socially shared regulation in learning. *British Journal of Educational Technology*, *n/a*(n/a). https://doi.org/10.1111/bjet.13325

Jasper, M. A. (2005). Using reflective writing within research. *Journal of Research in Nursing*, *10*(3), 247–260. https://doi.org/10.1177/174498710501000303

Jovchelovitch, S., & Bauer, M. W. (2000). Narrative interviewing. In M. W. Bauer & G. Gaskell (Eds.), *Qualitative Researching With Text, Image and Sound: A Practical Handbook* (pp. 57–74). Sage. http://www.sagepub.co.uk/

Kalina, C., & Powell, K. (2009). Cognitive and social constructivism: Developing tools for an effective classroom. *Education*, *130*(2), 241–250.

Kathpalia, S. S., & Heah, C. (2008). Reflective Writing: Insights into What Lies Beneath. *RELC Journal*, *39*(3), 300–317. https://doi.org/10.1177/0033688208096843

Kim, D., & Lim, C. (2018). Promoting socially shared metacognitive regulation in collaborative project-based learning: A framework for the design of structured guidance. *Teaching in Higher Education*, *23*(2), 194–211. https://doi.org/10.1080/13562517.2017.1379484

Kjellberg, M., O'CONNELL, M., Bergman, B., Stöhr, C., & Larsson, J. (2023). *Teachers' Reflections On Their Experiences Teaching Interdisciplinary Project-Based Courses*. European Society for Engineering Education (SEFI). https://doi.org/10.21427/1C6T-W684

Klaassen, R. G. (2018). Interdisciplinary education: A case study. *European Journal of Engineering Education*, *43*(6), 842–859. https://doi.org/10.1080/03043797.2018.1442417

Klein, J. T. (2010a). A taxonomy of interdisciplinarity. *The Oxford Handbook of Interdisciplinarity*, *15*(6), 15.

Klein, J. T. (2010b). *Creating Interdisciplinary Campus Cultures: A Model for Strength and Sustainability.* Chalmers Library E-book Collection.

https://research.ebsco.com/linkprocessor/plink?id=2e74f409-8061-3367-b3de-d2d08c237bb0

Kolmos, A., Holgaard, J. E., & Clausen, N. R. (2018). *Changed perspectives on engineering competence in the transition from engineering education to work*. 1–10.

Kolmos, A., Holgaard, J. E., Routhe, H. W., Winther, M., & Bertel, L. (2024). Interdisciplinary project types in engineering education. *European Journal of Engineering Education*, *49*(2), 257–282. https://doi.org/10.1080/03043797.2023.2267476

Kumbhar, S. R., Attar, A. C., & Telsang, M. T. (2018). Undergraduate research experience (URE): A new dimension in curricular redesign. *Journal of Engineering Education Transformations*, *2018*(Special Issue). Scopus. https://doi.org/10.16920/jeet/2018/v0i0/120927

Laal, M., & Ghodsi, S. M. (2012). Benefits of collaborative learning. *World Conference on Learning, Teaching & Administration - 2011*, *31*, 486–490. https://doi.org/10.1016/j.sbspro.2011.12.091

Lattuca, L. (2003). Creating interdisciplinarity: Grounded definitions from the college and university faculty. *History of Intellectual Culture*, *3*(1).

Lattuca, L. R., Knight, D. B., Ro, H. K., & Novoselich, B. J. (2017). Supporting the Development of Engineers' Interdisciplinary Competence. *Journal of Engineering Education*, *106*(1), 71–97. https://doi.org/10.1002/jee.20155

Lochmiller, C. R. (2021). Conducting thematic analysis with qualitative data. *The Qualitative Report*, *26*(6), 2029–2044.

Lopatto, D. (2004). Survey of Undergraduate Research Experiences (SURE): First Findings. *Cell Biology Education*, *3*(4), 270–277. https://doi.org/10.1187/cbe.04-07-0045

Lopatto, D. (2010). Undergraduate research as a high-impact student experience. *Peer Review*, *12*(2), 27.

MacLeod, M., & van der Veen, J. T. (2020). Scaffolding interdisciplinary project-based learning: A case study. *European Journal of Engineering Education*, *45*(3), 363–377. https://doi.org/10.1080/03043797.2019.1646210

Malmberg, J., Järvelä, S., & Järvenoja, H. (2017). Capturing temporal and sequential patterns of self-, co-, and socially shared regulation in the context of collaborative learning. *Contemporary Educational Psychology*, *49*, 160–174. https://doi.org/10.1016/j.cedpsych.2017.01.009

Malmberg, J., Järvelä, S., Järvenoja, H., & Panadero, E. (2015). Promoting socially shared regulation of learning in CSCL: Progress of socially shared regulation among high- and low-performing groups. *Computers in Human Behavior*, *52*, 562–572. https://doi.org/10.1016/j.chb.2015.03.082

Martins, F., Cezarino, L., & Liboni, L. (2023). Critical and Instrumental Perspectives of Interdisciplinarity for Business Education. In P. Singh, Y. Milshina, A. Batalhão, S. Sharma, & M. M. Hanafiah (Eds.), *The Route Towards Global Sustainability:*

Challenges and Management Practices (pp. 177–193). Springer International Publishing. https://doi.org/10.1007/978-3-031-10437-4_9

McCance, K. R., & Blanchard, M. (2024). Measuring the Interdisciplinarity and Collaboration Perceptions of U.S. Scientists, Engineers, and Educators. *AERA Open*, *10*, 23328584231218952. https://doi.org/10.1177/23328584231218952

McCaslin, M. L. (2008). *The SAGE Encyclopedia of Qualitative Research Methods* (Vol. 1–0).

McMurtry, A. (2011). The complexities of interdisciplinarity: Integrating two different perspectives on interdisciplinary research and education. *Complicity: An International Journal of Complexity and Education*, *8*(2).

Melzner, N., Greisel, M., Dresel, M., & Kollar, I. (2020). Regulating self-organized collaborative learning: The importance of homogeneous problem perception, immediacy and intensity of strategy use. *International Journal of Computer-Supported Collaborative Learning*, *15*(2), 149–177. https://doi.org/10.1007/s11412-020-09323-5

Menary, R. (2010). Cognitive Integration and the Extended Mind. In *The Extended Mind*. https://doi.org/10.7551/mitpress/9780262014038.003.0010

Miller, M., & Hadwin, A. (2015). Scripting and awareness tools for regulating collaborative learning: Changing the landscape of support in CSCL. *Computers in Human Behavior*, *52*, 573–588. https://doi.org/10.1016/j.chb.2015.01.050

Ming, X., van der Veen, J., & MacLeod, M. (2024). Competencies in interdisciplinary engineering education: Constructing perspectives on interdisciplinarity in a Q-sort study. *European Journal of Engineering Education*, 1–22. https://doi.org/10.1080/03043797.2024.2397419

Molenaar, I. (2022). The concept of hybrid human-AI regulation: Exemplifying how to support young learners' self-regulated learning. *Computers and Education: Artificial Intelligence*, *3*, 100070. https://doi.org/10.1016/j.caeai.2022.100070

Moon, K., & Blackman, D. (2014). A Guide to Understanding Social Science Research for Natural Scientists. *Conservation Biology*, *28*(5), 1167–1177. https://doi.org/10.1111/cobi.12326

Newell, W. H., Wentworth, J., & Sebberson, D. (2001). A theory of interdisciplinary studies. *Issues in Interdisciplinary Studies*, *19*, 1–25.

O'Donnell, A. M., & Hmelo-Silver, C. E. (2013). Introduction: What is collaborative learning?: An overview. *The International Handbook of Collaborative Learning*, 1–15.

Olivares-Donoso, R., & González, C. (2019). Undergraduate Research or Research-Based Courses: Which Is Most Beneficial for Science Students? *Research in Science Education*, *49*(1), 91–107. Scopus. https://doi.org/10.1007/s11165-017-9616-4

Packer, M. J., & Goicoechea, J. (2000). Sociocultural and Constructivist Theories of Learning: Ontology, Not Just Epistemology. *Educational Psychologist*, *35*(4), 227–241. https://doi.org/10.1207/S15326985EP3504_02

Panadero, E., Kirschner, P. A., Järvelä, S., Malmberg, J., & Järvenoja, H. (2015). How Individual Self-Regulation Affects Group Regulation and Performance: A Shared Regulation Intervention. *Small Group Research*, *46*(4), 431–454. https://doi.org/10.1177/1046496415591219

Pintrich, P. R. (2000). Chapter 14—The Role of Goal Orientation in Self-Regulated Learning. In M. Boekaerts, P. R. Pintrich, & M. Zeidner (Eds.), *Handbook of Self-Regulation* (pp. 451–502). Academic Press. https://doi.org/10.1016/B978-012109890-2/50043-3

Pintrich, P. R. (2004). A Conceptual Framework for Assessing Motivation and Self-Regulated Learning in College Students. *Educational Psychology Review*, *16*(4), 385–407. https://doi.org/10.1007/s10648-004-0006-x

Quackenbush, M., & Bol, L. (2020). Teacher Support of Co- and Socially-Shared Regulation of Learning in Middle School Mathematics Classrooms. *Frontiers in Education*, *Volume 5-2020*. https://www.frontiersin.org/journals/education/articles/10.3389/feduc.2020.580543

Repko, A. F. (2007). How the theories of common ground and cognitive interdisciplinarity are informing the debate on interdisciplinary integration. *Issues in Integrative Studies*, *25*, 1–31.

Repko, A. F., & Szostak, R. (2017). *Interdisciplinary research: Process and theory* (3rd ed.). Sage publications.

Rhee, H., Han, J., Lee, M., & Choi, Y.-W. (2020). Effects of interdisciplinary courses on future engineers' competency. *Higher Education, Skills and Work-Based Learning*, *10*(3), 467–479. Scopus. https://doi.org/10.1108/HESWBL-05-2019-0071

Ríos, I. de los, Cazorla, A., Díaz-Puente, J. M., & Yagüe, J. L. (2010). Project–based learning in engineering higher education: Two decades of teaching competences in real environments. *Innovation and Creativity in Education*, *2*(2), 1368–1378. https://doi.org/10.1016/j.sbspro.2010.03.202

Rogat, T. K., & Adams-Wiggins, K. R. (2015). Interrelation between regulatory and socioemotional processes within collaborative groups characterized by facilitative and directive other-regulation. *Computers in Human Behavior*, *52*, 589–600. https://doi.org/10.1016/j.chb.2015.01.026

Rogat, T. K., & Linnenbrink-Garcia, L. (2011). Socially Shared Regulation in Collaborative Groups: An Analysis of the Interplay Between Quality of Social Regulation and Group Processes. *Cognition and Instruction*, *29*(4), 375–415. https://doi.org/10.1080/07370008.2011.607930

Scager, K., Boonstra, J., Peeters, T., Vulperhorst, J., & Wiegant, F. (2016). Collaborative Learning in Higher Education: Evoking Positive Interdependence. *CBE—Life Sciences Education*, *15*(4), ar69. https://doi.org/10.1187/cbe.16-07-0219

Scanlan, J. M., Care, W. D., & Udod, S. (2002). Unravelling the unknowns of reflection in classroom teaching. *Journal of Advanced Nursing*, *38*(2), 136–143.

Seiradakis, E., & Spantidakis, I. (2019). Socially-Shared Metacognitive Regulation Episodes between Undergraduate Engineering Students during a Collaborative Genre Analysis Task in an English for Academic Purposes Course. *English Language Teaching*, *12*(6), 217–225.

Singer, J., Marx, R. W., Krajcik, J., & Clay Chambers, J. (2000). Constructing extended inquiry projects: Curriculum materials for science education reform. *Educational Psychologist*, *35*(3), 165–178.

Stahl, G. (2013). Theories of cognition in collaborative learning. *The International Handbook of Collaborative Learning*, 74–90.

Stentoft, D. (2017). From saying to doing interdisciplinary learning: Is problem-based learning the answer? *Active Learning in Higher Education*, *18*(1), 51–61. https://doi.org/10.1177/1469787417693510

Stoller, A. (2020). A Case for Critical Interdisciplinarity: Interdisciplinarity as Democratic Education. *Issues in Interdisciplinary Studies*, *38*, 33–56.

Sulla, F., Monacis, D., & Limone, P. (2023). A systematic review of the role of teachers' support in promoting socially shared regulatory strategies for learning. *Frontiers in Psychology*, *14*. https://www.frontiersin.org/journals/psychology/articles/10.3389/fpsyg.2023.1208012

Summers, M., & Volet, S. (2010). Group work does not necessarily equal collaborative learning: Evidence from observations and self-reports. *European Journal of Psychology of Education*, *25*(4), 473–492.

Swain, J. (2021). *A Hybrid Approach to Thematic Analysis in Qualitative Research: Using a Practical Example*. https://doi.org/10.4135/9781526435477

Ucan, S., & Webb, M. (2015). Social Regulation of Learning During Collaborative Inquiry Learning in Science: How does it emerge and what are its functions? *International Journal of Science Education*, *37*(15), 2503–2532. https://doi.org/10.1080/09500693.2015.1083634

Vauras, M., Iiskala, T., Kajamies, A., Kinnunen, R., & Lehtinen, E. (2003). Shared-regulation and motivation of collaborating peers: A case analysis. *Psychologia*, *46*(1), 19–37.

Volet, S., Summers, M., & Thurman, J. (2009). High-level co-regulation in collaborative learning: How does it emerge and how is it sustained? *Learning and Instruction*, *19*(2), 128–143. https://doi.org/10.1016/j.learninstruc.2008.03.001

Vuopala, E., Näykki, P., Isohätälä, J., & Järvelä, S. (2019). Knowledge co-construction activities and task-related monitoring in scripted collaborative learning. *Learning, Culture and Social Interaction*, *21*, 234–249. https://doi.org/10.1016/j.lcsi.2019.03.011

Wallin, P. (2020). Student perspectives on co-creating timescapes in interdisciplinary projects. *Teaching in Higher Education*, *25*(6), 766–781. https://doi.org/10.1080/13562517.2020.1777962

Wallin, P., & Adawi, T. (2018). The reflective diary as a method for the formative assessment of self-regulated learning. *European Journal of Engineering Education*, *43*(4), 507–521. https://doi.org/10.1080/03043797.2017.1290585

Wallin, P., Adawi, T., & Gold, J. (2020). Involving Undergraduate Students in Research: Practices, Promises and Pointers. *1-12*. https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2677948

Wallin, P., Lyng, R., Sortland, B., & Veine, S. (2017). *Experts in teamwork-A large scale course for interdisciplinary learning and collaboration*. 1–11.

Wang, L. (2011). Sociocultural Learning Theories and Information Literacy Teaching Activities in Higher Education. *Reference & User Services Quarterly; Vol 47, No 2 (2007): WinterDO - 10.5860/Rusq.47n2.149*. https://journals.ala.org/index.php/rusq/article/view/3775

Welch IV, J. (2011). The Emergence of Interdisciplinarity from Epistemological Thought. *Issues in Integrative Studies*, *29*, 1–39.

Winne, P., & Hadwin, A. (2008). *The weave of motivation and self-regulated learning. In DH Schunk & BJ Zimmerman (eds.), Motivation and self-regulated learning: Theory, research, and applications (pp. 297-314)*.

Zimmerman, B. J. (2000). Attaining self-regulation: A social cognitive perspective. In *Handbook of self-regulation* (pp. 13–39). Academic Press. https://doi.org/10.1016/B978-012109890-2/50031-7

Zimmerman, B. J. (2008). Goal setting: A key proactive source of academic self-regulation. In *Motivation and self-regulated learning: Theory, research, and applications.* (pp. 267–295). Lawrence Erlbaum Associates Publishers.

Zimmerman, B. J. (2015). Self-Regulated Learning: Theories, Measures, and Outcomes. *International Encyclopedia of the Social & Behavioral Sciences*, 541–546. https://doi.org/10.1016/B978-0-08-097086-8.26060-1

Zimmerman, B. J., & Moylan, A. R. (2009). Self-regulation: Where metacognition and motivation intersect. In *Handbook of metacognition in education* (pp. 311–328). Routledge.