

Exploring the applications of plasma physics in the semiconductor industry through challenge-based learning

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ABSTRACT

This study investigates the integration of Challenge-Based Learning (CBL) into a master-level plasma physics course, with the aim of bridging the gap between academic research and industrial applications in the semiconductor sector. The course design centred on reverse-engineering fabrication processes for advanced nanoelectronics, challenging students to apply plasma processing concepts to authentic, industry-relevant problems. Using a mixed-methods design (surveys and interviews), we evaluated the impact of CBL on student engagement, skill development, and knowledge integration. Results show that students valued the open-ended nature of the challenge, reporting increased motivation, deeper understanding of theoretical concepts, and improved problem-solving, navigation of literature, and critical evaluation of diverse information sources. While many students initially found the project overwhelming, structured scaffolding through weekly feedback, peer review and mentoring helped sustain motivation and build confidence. The findings demonstrate that CBL can be effectively adapted to conceptually dense courses, even without direct industry collaboration. We demonstrate that combining open-ended challenges with structured theoretical instruction provides a balanced approach that prepares students with both disciplinary expertise and transferable skills essential to today's rapidly evolving technological landscape.

KEYWORDS

Physics education, Challenge-based learning, Industry challenges, Plasma processing, Engineering education

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Introduction

The accelerating pace of technological innovation and its application in industry necessitates closer alignment between academic research and industry practices, especially in fields at the forefront of technological advancement, such as nanoelectronics, biotechnology and renewable energy. This alignment is crucial for fostering innovation and addressing real-world challenges. However, a persistent gap remains due to differing priorities: academia emphasises fundamental theory and discovery, while industry focuses on practical solutions and scalability (e.g., Perkmann et al. 2013).

Efforts to bridge this divide are increasingly focusing on educational models that integrate practical experience and collaborative learning environments. Concurrently, the landscape of higher education is undergoing a significant transformation, driven by the need to prepare students with the skills and knowledge required to navigate the complexities of the modern world (Shemyhon 2024, Tomeo-Reyes, Chai and Ravishankar 2025). In this context, educational innovation has emerged as a critical area of focus, with Challenge-Based Learning (CBL) standing out as a promising pedagogical approach that aligns academic learning with real-world applications (Gallagher and Savage 2020, Membrillo-Hernández et al. 2021). The CBL approach to education, characterised by its student-centred, collaborative, and problem-solving approach, offers a framework for learners to engage deeply with subject matter through the lens of real-world challenges (Lazendic-Galloway et al. 2021, Höffken & Lazendic-Galloway 2024). This pedagogical approach not only aims to enhance academic learning, but also seeks to develop essential skills such as critical thinking, communication and collaboration (Clegg & Diller 2019). Furthermore, CBL has the potential to foster a deeper connection between academic research and practical applications (e.g., Reymen et al. 2022, Gumuscu et al. 2024).

Despite its growing popularity, applying CBL in advanced science courses, especially in domains that require highly specialised knowledge, remains relatively underexplored. Plasma physics, a field at the forefront of scientific and technological innovation, offers a unique context for applying CBL due to its dynamic nature and the continuous emergence of new technologies and applications (Chen 2018). Embedding CBL in such contexts raises important pedagogical questions: How can students be guided to connect abstract theoretical concepts with industrial practice? And how can this be achieved when direct collaboration with industry is limited by confidentiality and intellectual property restrictions?

This paper addresses these questions through the case of a master-level applied physics course. By engaging students in reverse-engineering device fabrication processes, the course created a structured yet open-ended environment in which learners applied theoretical knowledge to real-world industrial problems. Through mixed-methods analysis of surveys and interviews, this study explores how CBL supports student engagement, skill development and knowledge integration. We argue that this case demonstrates how CBL can be successfully adapted to concept-heavy STEM courses, even without direct industry involvement, and how a hybrid model combining CBL with structured assessment can effectively balance disciplinary depth with professional relevance.

Literature review

One of the longstanding challenges in higher education, particularly in science and engineering disciplines, is the disconnect between academic research and industry applications (Felder & Brent 2016, Graham 2018). While universities focus on theoretical advancements and fundamental research, industries prioritise applied knowledge and innovation for commercial success (Perkmann et al. 2013, Henderson et al. 2018). Bridging this gap necessitates educational approaches that effectively integrate industry perspectives and real-world applications into academic curricula.

Project-based and challenge-based learning strategies have shown considerable promise in addressing this divide by immersing students in authentic, industry-relevant problems and scenarios (Kolmos &

de Graaff, 2014, Reymen et al. 2022). This approach not only enhances students' technical competencies but also develops crucial professional skills, such as teamwork, problem-solving and innovation, which are essential for modern engineering careers.

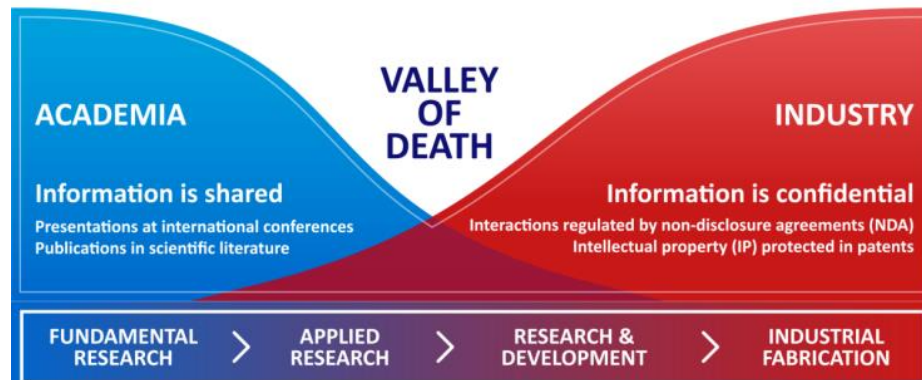


Figure 1. Illustration of the "Valley of Death" between academia and industry across the research-to-innovation pipeline. The graphic highlights the contrast in knowledge-sharing practices: academia emphasises openness through publications and conference presentations, while industry prioritises confidentiality through intellectual property protection and non-disclosure agreements. This divide often creates barriers in translating fundamental and applied research into scalable industrial fabrication. Adapted from United States Government Accountability Office (2014).

In the context of applied plasma physics, this integration is particularly critical. Given the complexity, interdisciplinary nature and rapid technological evolution inherent in plasma technologies (Lieberman & Lichtenberg 2005), students require a robust theoretical foundation combined with practical experience to address industry-driven challenges (Roth 2021). However, a significant barrier to integrating industry knowledge into educational settings arises from contrasting knowledge-sharing approaches, as shown in Fig. 1. Academic research typically emphasises the open dissemination of findings through publications, posters and presentations, fostering a collaborative, international exchange of ideas (e.g., Boyer 1990, Subramanyam 2013). Conversely, industry knowledge is frequently proprietary and confidential, constrained by intellectual property concerns aimed at maintaining competitive advantage (e.g., Chesbrough 2020). Companies often restrict the dissemination of detailed methodologies and results until proper protection is secured, creating a distinct knowledge-sharing gap between academia and industry.

Addressing this critical gap requires deliberate instructional strategies that facilitate mutually beneficial collaborations, allowing students to gain practical insights while safeguarding industrial intellectual property interests. Therefore, CBL, with its emphasis on real-world problem-solving and stakeholder collaboration, offers a promising educational framework to effectively bridge this divide. Most university courses focus on acquiring knowledge, and some also focus on acquiring practical skills, such as programming or conducting experiments. In the course examined in this paper, students learn to deal with the openness of a real-world project. For future employers, this skill is very valuable, since, in general, the outcome of a project in a working environment is not known in advance either. Furthermore, students learn to be creative in gathering and combining information from different sources. Such skills are useful, even when one does not continue in the same field of work.

A complementary framework is Reverse Engineering Pedagogy (REP), which centres on deconstructing existing systems or products to uncover their underlying principles before designing or

improving solutions (López et al. 2019, Wiesen et al. 2018). REP has gained traction in STEM education, particularly at the K–12 and undergraduate levels, for its ability to reduce cognitive load and provide concrete entry points into abstract or complex concepts (Zhong, Liu & Li 2024). For instance, studies in early STEM education have shown that REP fosters a deeper understanding of scientific principles, enhances computational thinking, and supports skill development by helping students focus on analysing existing artefacts rather than producing novel solutions from scratch (López et al. 2019). These benefits make REP an effective scaffold, especially for novice learners who may struggle with open-ended or ill-structured problems.

However, the context explored in this study (graduate-level plasma physics) poses a fundamentally different pedagogical challenge. In contrast to undergraduate implementations, where REP is often used to simplify learning and lower cognitive demand, this course leverages REP in a more complex and nuanced way. Students were tasked with reverse-engineering sophisticated semiconductor fabrication processes, requiring them to engage deeply with advanced theoretical content, navigate diverse technical literature, and synthesise fragmented, sometimes proprietary, information.

Context

Technical knowledge and skills are integral to engineering professions. In the Plasma Processing Science & Technology (PPST) course, which is part of the MSc program in Applied Physics at the Eindhoven University of Technology (TU/e), students learn about the state of the art in plasma processing. Furthermore, they learn the techniques used to make familiar devices such as smartphones and laptops. The course is delivered over a period of one quartile (ten weeks in length), of which seven weeks have eight contact hours per week. The course consists of lectures (4 hours/week), guided self-study time (2 hours/week), and group discussions on the project (2 hours/week), as shown in Table 1. There is also one lab session designed to let students experience firsthand the different plasma processing approaches covered in the course material. The project accounts for 40% of the total grade, while the written exam accounts for 60%. This is an elective course that runs once per year. Students typically enrol in the course during the first year of the two-year MSc program. In parallel with this course, students generally take two additional courses of comparable workload. For project submission and peer-review activities, a digital platform is used to manage submissions and feedback. This system streamlines the review process and reduces the administrative workload for teaching staff.

Because plasma processing is an evolving field, it is important to teach students the skills of lifelong learning and ongoing professional development. A project component in this course was redesigned using CBL approaches to engage students hands-on with the latest developments in plasma processing research and industry applications. The lecturers of the course (which includes the last two authors) were motivated to include a challenge in the course in order to bridge the gap that exists between the works of university research groups and applications in the semiconductor industry, and for students to understand the broader context of the knowledge obtained from the lectures.

At the core of the CBL implementation is a challenge that asks students to determine which processing technologies could fabricate a component of a computer chip (e.g., the processor or the memory chip in the latest smartphone). To this end, the students are asked to unravel (i.e., reverse-engineer) the process flows for fabricating a specific device structure. An abstract from a recent conference on device engineering is used as a “pitch” or starting point, which enables students to work on the latest developments in the field. The students chose the challenge they would like to work on individually, and those who chose similar challenges formed a small group. Every week, the students discuss their findings, ideas, and struggles in their group, which is mentored by a tutor (a PhD student from the lecturers' research group). The two lecturers are also present in the room during the discussion and available for consultation. Because much of the course content closely aligns with the instructors'

ongoing research, preparation primarily involves adapting existing research materials rather than creating new content and therefore does not impose a substantial additional workload.

Table 1. A typical schedule of the learning activities in the course. Lecture sessions are represented by blue blocks (4 hours/week), and red blocks represent guided self-study (2 hours/week) and group discussions during project sessions (2 hours/week). The lab training is marked with the green block.

	Monday 13:30 - 17:15		Wednesday 8:45 - 12:30
Feb 7	1. Introduction <i>Guided self-study</i>	Feb 9	1. Introduction <i>Group discussions project</i>
Feb 14	2. Surface science <i>Guided self-study</i>	Feb 16	2. Surface science <i>Group discussions project</i>
Feb 21	3. Deposition <i>Guided self-study</i>	Feb 23	3. Deposition <i>Group discussions project</i>
Mar 7	4. Etching <i>Guided self-study</i>	Mar 9	4. Etching <i>Group discussions project</i>
Mar 14	Lab training <i>PMP labs & cleanroom</i>	Mar 16	5. Patterning
Mar 21	6. 2D materials	Mar 23	Evaluation assignment <i>Group presentations</i>
Mar 28	7. Atomic-scale processing <i>Guided self-study</i>	Mar 30	7. Atomic-scale processing <i>Guided self-study</i>

For their project, the students combine information from various sources (e.g., lecture notes/materials, patents, scientific literature) to provide an overview of the sequence of plasma processing steps that *could be* employed to fabricate the device. Since there are multiple possible ways in which the fabrication can be achieved, the process and the outcome of solving the challenge are not defined, in line with CBL characteristics (e.g., Gallagher & Savage 2020). Importantly, there is no single correct answer, and even the lecturers do not know precisely how the fabrication process is carried out. This is because the students are effectively reverse-engineering how plasma processing could be applied to create an industry-specific product whose fabrication methods are not publicly disclosed due to intellectual property protections. Therefore, the course differs somewhat from a typical CBL course, in which students collaborate directly with industry. In this course, the students indirectly engage with stakeholders by studying real-world artefacts (electronic devices) and using authentic materials (conference papers, patents, technical literature). They also engage with the industry's outputs and practices. Through reverse-engineering, they are exposed to the decision-making process, grounded in real constraints and the methods used by real professionals. Although the engagement with industry is indirect, the activity fully aligns with CBL principles: students are presented with an open-ended, real-world challenge without a predefined research question or a prescribed methodology. They must navigate the uncertainty of the problem space, independently define their investigative strategies, critically interpret authentic industry outputs (such as patents and conference papers), and iteratively refine their hypotheses, mirroring the skills and mindset required in professional practice.

Furthermore, students are taught the culture and skills of peer review in scientific publications. To illustrate this process, the lecturers share examples of peer evaluations and rebuttal letters from their own manuscript submissions. As part of their training, students prepare individual project reports and

are asked to submit a preliminary draft two weeks before the due date. Two students from different topic groups are then asked to review this initial draft. Following this peer review cycle, students refine and submit their final project reports for grading. The peer review serves two purposes: first, it helps students improve their reports, and second, it exposes them to additional ideas for shaping their reports.

Finally, a presentation session is organised toward the end of the course, during which the groups share what they discovered while working on their projects. Although there is no grade associated with this presentation, it can be a useful opportunity to solicit extra feedback from lecturers and other students before finishing the final project report. Even though the presentations do not go into great detail, hearing a variety of topics provides insight into why the creation of nanoelectronics is exciting. This process is also an important component of CBL because lecturers act as *co-learners* and gain new knowledge through their dialogues with students. Since students approach topics from a different angle than lecturers, they often offer insights that lecturers can learn from.

Method

This study employs a mixed-methods approach, integrating quantitative and qualitative methods. Our study is guided by three research questions: (RQ1) How does the CBL course approach help students bridge the gap between academic research and industry applications? (RQ2) How does the CBL course approach help students in the identification and navigation of relevant scientific and industrial literature? (RQ3) What are the benefits of using the CBL approach in this course, from the students' perspective?

The primary instrument for the study was a survey designed to collect both types of data. Additionally, we conducted in-depth interviews with select students to gain a more comprehensive understanding of their experiences in the course. Before data collection, we obtained the necessary ethics approval (no. ERB2021ESOE18), ensuring that all research activities complied with ethical standards.

The participant cohort consisted of students enrolled in a master-level course during the 2021-2022 academic year, spanning one quartile (10 weeks). The course had a total enrolment of 25 students. Of these, 21 students completed the survey and consented to the use of their data for research purposes. The survey was distributed electronically in the last week of the course during a scheduled class break, when the primary researcher also invited students to participate in follow-up interviews. Of all the participants, three volunteered for in-depth interviews to elaborate on their course experiences.

The survey comprised seven closed-ended questions, with various Likert scales used to quantify responses (see Results section). These questions were crafted to explore several key aspects of the course. Firstly, we sought to understand how the project contributed to learning in the course, how it facilitated student engagement with the subject matter and how students perceived the open-ended nature of the project. This included assessing whether the project enhanced students' understanding of theoretical concepts presented in lectures and contributed to the development of the specific skills outlined in the course objectives. The peer learning aspect of the project was also investigated, especially the extent and nature of the guidance students found necessary for their success. To complement these quantitative measures, the survey included two open-ended questions. One question asked students to explain why they might recommend the course to peers, offering insights into its perceived value and appeal. The other question gave students an opportunity to suggest improvements to the course, thereby directly contributing to its future development.

The coding procedure for analysing responses to the open-ended survey questions and interviews followed the standard thematic analysis procedure (Braun & Clarke 2006) to ensure rigorous, systematic analysis. The interviews were transcribed and anonymised for the analysis. This involved

developing a coding scheme that identified key themes and patterns in the data. The coding process was iterative, involving multiple rounds of review to ensure accurate and comprehensive interpretations. This qualitative analysis aimed to provide deeper insights into the students' experiences and perceptions, complementing the quantitative data and enriching the understanding of the course's impact on student learning and engagement.

One limitation of this study is the relatively small sample size, drawn from a single course at one institution, which may limit the generalizability of the findings. However, studies of educational innovation often contribute by adding breadth of context, such as discipline-specific, level-specific or institution-specific insights, that enrich the overall understanding of educational approaches like CBL. In this case, the study provides valuable evidence of how CBL can be effectively adapted to a conceptually dense, master-level disciplinary course. Future research could investigate the long-term impact of CBL on students' career trajectories, particularly in fields where rapid technological change demands agility, interdisciplinarity and continuous learning.

Results

Findings from the quantitative data

The survey includes questions designed to capture students' experiences and perceptions of the course, the project, and the learning process.

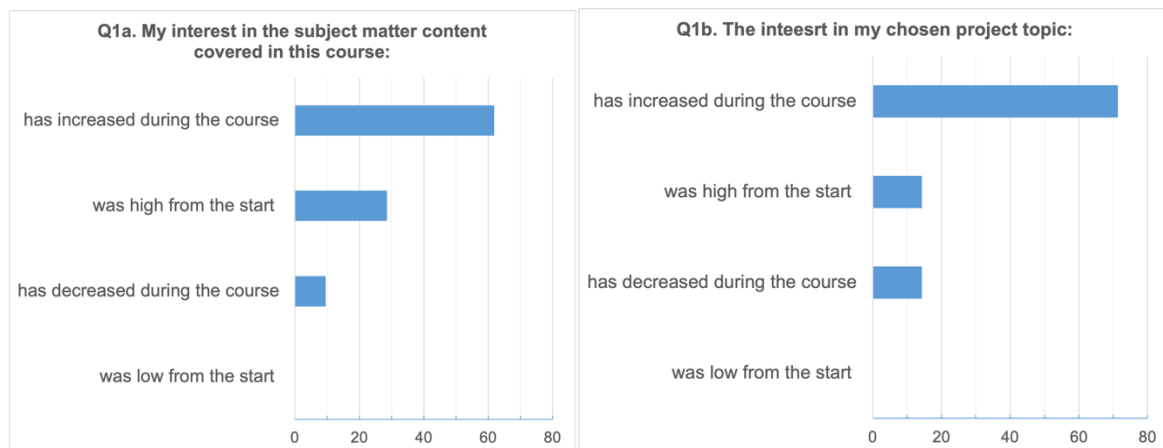


Figure 2. The survey responses to Q1 questions are presented as fractional frequencies of students' agreement with each statement (N=21). Axis values are expressed as percentages.

Responses to the first question suggest a general increase in interest in both the subject matter and project topics, highlighting the course's success in engaging students (Fig. 2). The students chose themselves the topic of their challenge to solve for the project, and, for 71% of the students, interest increased as they worked on solving the challenge. For a small number of students, interest in the course and their project topic decreased over time. Around 29% of the students already had a high interest in the topics covered, and for 62%, that interest increased throughout the course.

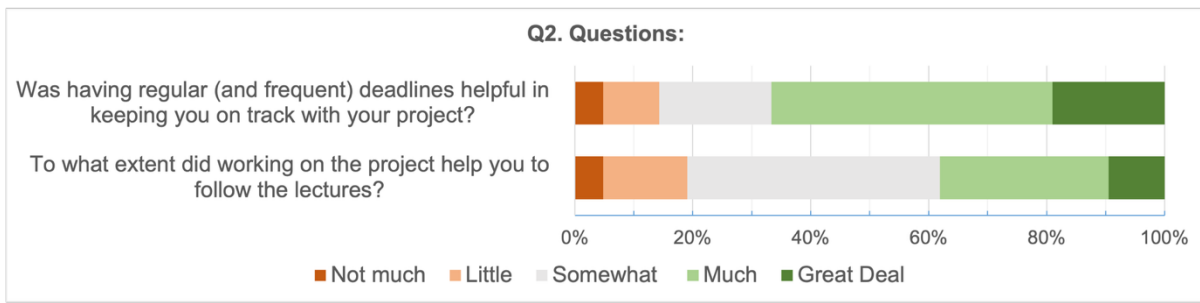


Figure 3. Survey responses to Q2, reported as fractional frequencies (N = 21). Agreement is indicated in green shades, disagreement in orange shades, and neutral responses in grey.

The open-ended nature of the challenge requires adequate support for learners. Scaffolding for student work was provided through weekly meetings. For these group discussions, students needed to prepare a short presentation on what they had found and learned about their challenge so far. Other students in the group and their tutor would provide feedback and discuss further steps. While the tutor stayed with the individual student groups, the lecturers would walk between the groups, answering questions or providing advice as needed. These weekly “deadlines” for preparing a short presentation are found to be highly beneficial (“much” and “great deal” responses) by 67% of the students, moderately (“somewhat” and “little” responses) beneficial by 28% of the students, and not beneficial at all by 5% of the students (Fig. 3). In terms of cross-learning between the project and the course content 38% of the students found the project was significantly helpful, 57% found it moderately helpful, and only 5% found it not helpful at all.

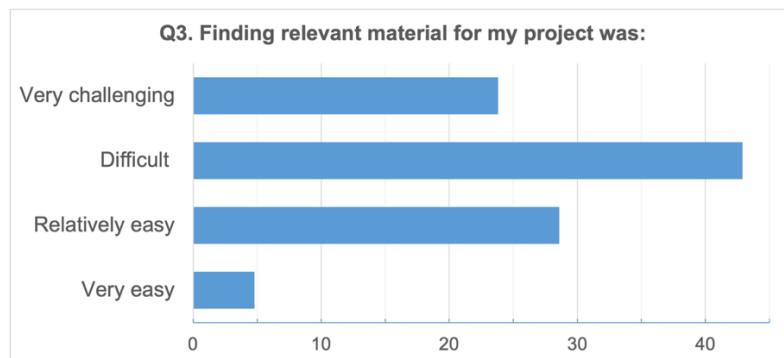


Figure 4a. The survey responses to Q3 are presented as fractional frequencies of students’ agreement with the statements (N=21). Axis values are expressed as percentages.

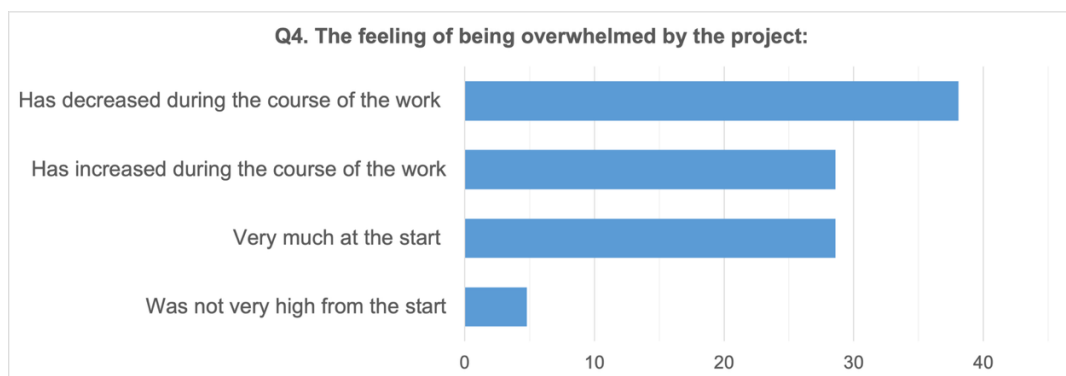


Figure 4b. The survey responses to Q4 are presented as fractional frequencies of students’ agreement with the statements (N=21). Axis values are expressed as percentages.

Since the project required the students to search for adequate literature and sift through various industry materials (company websites, patents, etc), 43% of the students felt that finding the relevant material was difficult, and 24% found it very challenging (Fig. 4a). Indeed, skills needed to bridge the gap between research and industry involve locating and interpreting technical information across diverse sources, and also critically evaluating the credibility, relevance and applicability of that information. Therefore, the course aims to develop these skills in students through scaffolding and feedback.

A CBL approach to learning often starts with a very open-ended question (e.g., Malmqvist et al. 2015), which can be unfamiliar and overwhelming to students. Indeed, 28% of the students found the project overwhelming at the start; for another 38%, this decreased during the course, but for 29% it increased (Fig. 4b).

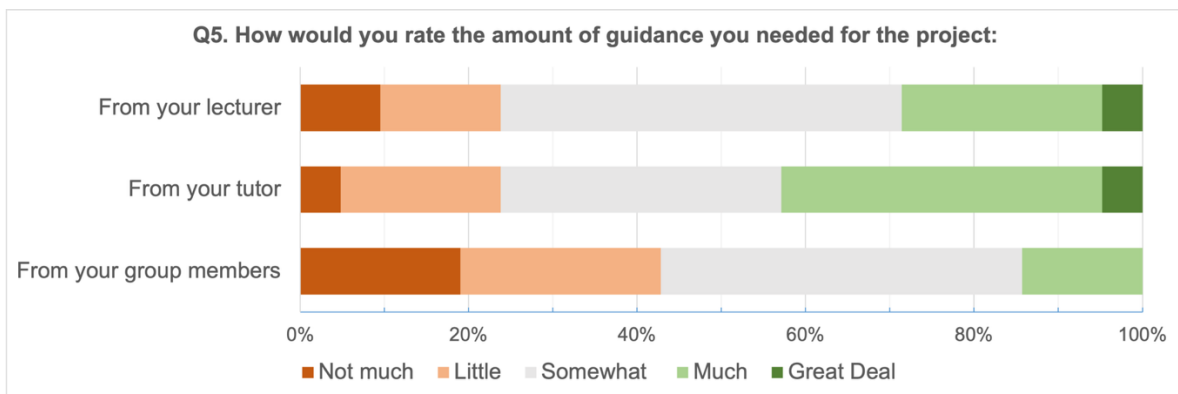


Figure 5. Survey responses to Q5, reported as fractional frequencies (N = 21). Agreement is indicated in green shades, disagreement in orange shades, and neutral responses in grey.

While the decrease in overwhelm is expected as students become more familiar with this way of working, for some students, other factors contributed to greater feelings of overwhelm. In such situations, the students rely on support from others. In this case, the students turned for guidance to tutors and lecturers and moderately from their peers (Fig. 5). Furthermore, most students found discussing their project with peers and tutors helpful, felt encouraged to share their ideas and provide peer feedback, and felt encouraged to seek help when they encountered problems and roadblocks (Fig. 6).

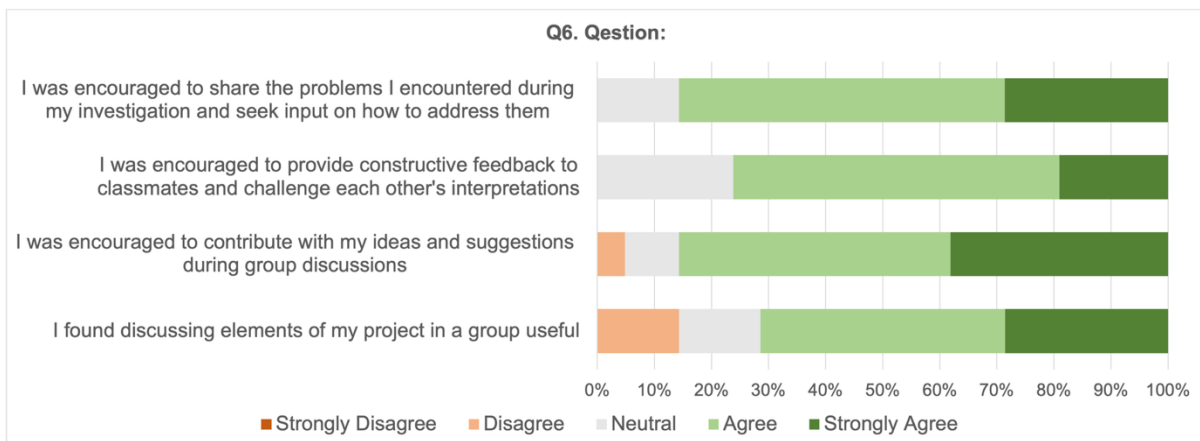


Figure 6. Survey responses to Q6, reported as fractional frequencies (N = 21). Agreement is indicated in green shades, disagreement in orange shades, and neutral responses in grey.

In terms of skill development, 52% of the students agreed that the project helped them gain useful skills for their future careers, with 76% of the students agreeing that they increased their ability to find relevant information, and 71% of the students found that the project helped them become more critical of different types of information sources (Fig. 7).

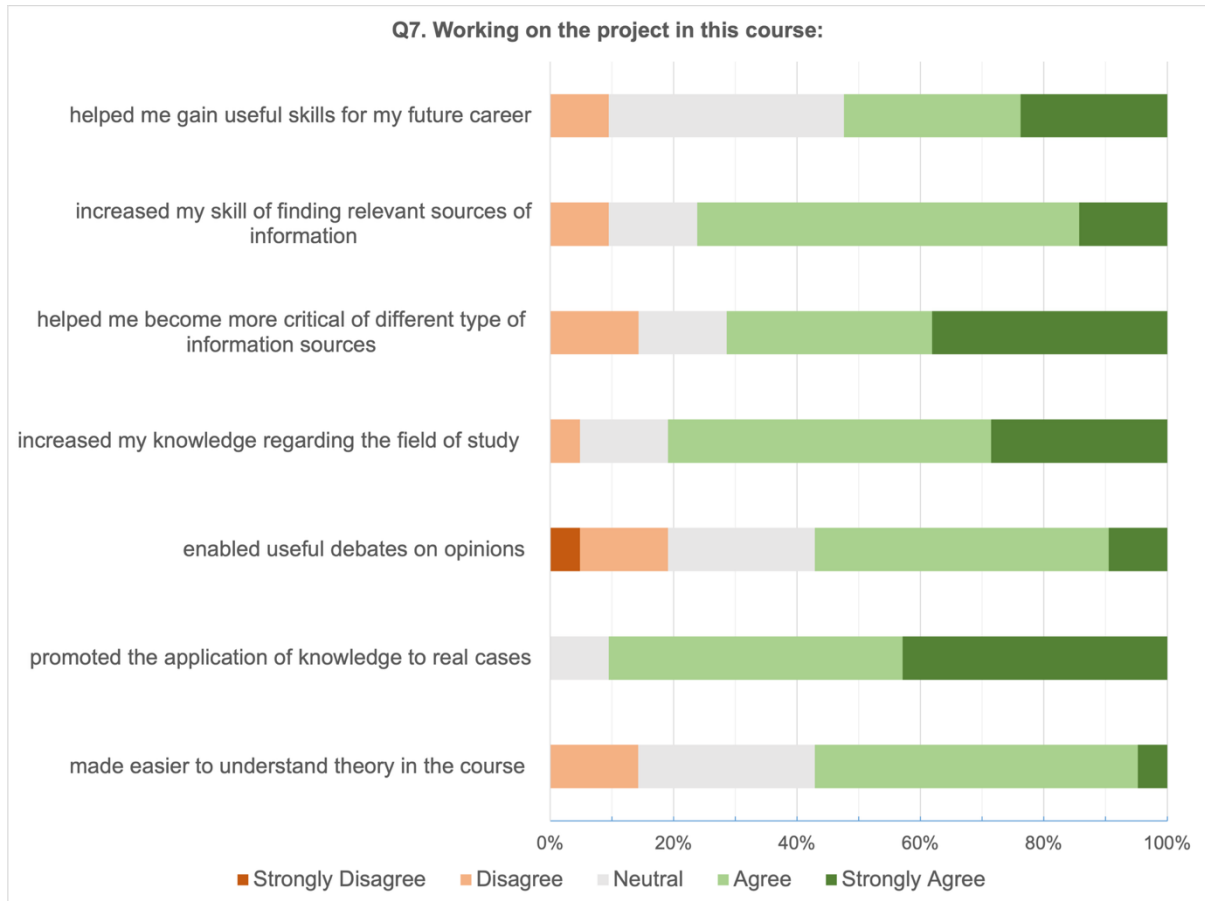


Figure 7. Survey responses to Q7, reported as fractional frequencies (N = 21). Agreement is indicated in green shades, disagreement in orange shades, and neutral responses in grey.

Figure 7 also shows that, regarding knowledge acquisition, 81% of the students agreed that the project increased their knowledge of the field of study. Additionally, the project was reported to promote the application of theoretical knowledge to real-world cases, with over 90% of students agreeing that it enabled them to contextualise their learning through authentic challenges. About 57% of students indicated that the course facilitated useful debates and the exchange of ideas, helping them refine their understanding through peer feedback and group discussions. Furthermore, 81% of students agreed that the project made it easier to understand the course's theoretical concepts, highlighting the value of integrating hands-on, exploratory work with formal instruction.

Results from open-ended survey questions

The first open-ended question included in the survey was “Would you recommend this course to other students and why?” We identify the following themes (the number in brackets denote the number of instances of the theme): enjoying the open-ended nature of the project (3), enjoying application of the theory or synergy with the theory (4), because it’s something different/new in respect to other courses (2), because of better engagement in the course (1), because it involves a real-life example (1), and because of helpful group discussions (1). In the words of the students:

“Open character and the fact that no answer to the problem is wrong or right, but it is based on educated guesses with good argumentation leading to the most logical solution.”

“Very nice variation from the standard only exam approach. The project was intimidating at first, but as time progressed, the subject became clearer. And by the time I had to write my report, I felt that I already had the information I needed from the earlier investigation sessions, which was really nice. Seeing subjects from the lecture applied in papers, and the paper information returning in the lecture, greatly motivated me and gave me a sense of cohesion.”

The second open-ended questions in the survey was “Do you have any suggestions for improvement of the assignment or any other general feedback?”, and the main issues that students mentioned were that the project is too time demanding for a 5 ECTS course (6), that the concepts should be covered first in the lectures (1), and that information about the project should be better communicated (2). The lecturers found this feedback very useful and addressed these issues in subsequent runs of the course by introducing the project topics earlier, giving students an overview of all the project phases in week 1, and setting clearer expectations for the workload.

Results from the interviews

Qualitative analysis of the interview data revealed several recurring themes that provide insight into student experiences with the CBL approach in the plasma physics course. These themes, summarised in Table 2, reflect both cognitive and affective dimensions of learning and highlight the course’s influence on skill development, motivation, and knowledge integration.

Table 2. The main themes identified from the interviews.

Theme	Description
Interest and motivation to join this course	Students expressed their interest in physics and the motivation behind choosing their field of study, highlighting a desire to understand the world and apply their knowledge in real-world settings.
Enhanced engagement and ownership	Students felt more involved and invested in the learning process when working on real-world problems, despite some constraints.
Peer collaboration	The students appreciating the opportunity to work in groups, share findings and receive feedback.
Knowledge acquisition	The students reflected on knowledge gained through the project versus lectures and preparing for the exam.

Interest and motivation: Students expressed a strong initial interest in the course, driven by a desire to connect their physics background with real-world applications. The CBL structure was seen as a refreshing approach, emphasising the appeal of seeing practical relevance in complex subject matter:

“It really sparked my interest because I really liked that they talked about different fabricating procedures. We got to view the clean room, for example. And then when you stop to think about it, just thinking, “Oh wait, we’re talking about something that is the size of 20 atoms here!” So, how do you make something that’s 20 atoms broad, you know? And I like that – the general direction of the challenges that they face and try to solve. I think it’s quite intriguing.”

Enhanced engagement and ownership: The CBL framework fostered a sense of ownership over the learning process. Students felt personally invested in their projects, which led to sustained motivation and deeper engagement:

“With exam kind of learning, it's more passive learning, I'd say. And for me, it doesn't stick. I obviously work through the exercises, and I pay attention during the lectures, and the basics remain, but over time, it just kind of leaves my head. Whereas with the project, it's something you, worked on. So on one hand, it's also precious to you because it's your research. So you want pay attention to it. And well, that makes it all the more interesting.”

“I am very much in favour of having this project throughout the course, where you have to apply your knowledge directly to a new technology. And also the fact that it was a new technology or idea, that was really nice. Because that meant that there weren't a lot of papers and that you really had to think for yourself instead of just scoping information.”

Peer collaboration and feedback: While the structure was not built around collaborative group work, peer engagement during weekly group discussions played a meaningful role. Students appreciated the opportunity to receive feedback and refine their thinking through informal peer interaction:

“The fact that you were in a group with other people and that you were presenting to these other people was good because you're working on your presentation skills, and you can get comments on your part.”

“You could help each other in how you look for sources and how you create your presentations.”

“You had these weekly meetings on Wednesday and you had to kind of pitch what you found out to the rest of your group. Which was nice because it was kind of a way to simulate what they do in research groups as well. So that was nice.”

Knowledge acquisition and integration: CBL allowed a deeper understanding of the course content through application, helping theoretical concepts stick. The students also distinguished between the types of knowledge gained from the project and the lectures. The project was described as fostering a deeper, contextual understanding, while lectures supported foundational and procedural knowledge:

“So for me, I really like the fact that this course really gives a practical outlook, really gives a view of the corporate world and the implementation of the stuff that we learn [in courses] into a real field. And I really like that. [In other courses], we never go deep on the practical stuff. Here, it really felt like everything was coming together.”

“I thought it was very smartly done that they used the course to understand the in-depth material, but I can see that the exam itself forces you to go back to all the stuff, the general overview of the material. So while the report for me gives a very in-depth look at a specific subject in a specific field, the exam is naturally there because you need to understand the general concepts as well. So I get why they're both there. And I think in that aspect, they reinforced each other because I understand the exam material better, because I had an in-depth experience where I had to sometimes look things up. So things come back in context. But I also understood the in-depth things better because I had seen things in lectures. So for me, they do synergise really well.”

Discussion

This study aimed to understand the impact of CBL on students' engagement and learning in an advanced physics course with a strong industry focus. The findings from both quantitative and qualitative data confirm that CBL can be highly effective in fostering engagement, deep learning (as opposed to surface learning), and the development of transferable skills when carefully adapted to the needs of conceptually dense and discipline-specific contexts.

Bridging academic research and industry applications

The first research question explored how CBL helps students bridge the gap between academic research and industry practice. The course design, centred on reverse-engineering an industry-relevant device, provided students with a realistic and authentic challenge. Rather than working directly with disclosed industrial data, often limited by intellectual property protections (Chesbrough 2020, Perkmann et al. 2013), students engaged indirectly with industry outputs through patents, technical literature, and conference abstracts. This approach simulated the ambiguity and open-endedness of real-world problem-solving, a hallmark of effective CBL (Gallagher & Savage 2020, Reymen et al. 2022).

Students found this connection to industry both motivating and eye-opening. Survey and interview data revealed that working on a challenge without a predefined solution helped them appreciate the complexity of industrial fabrication and the relevance of academic knowledge to professional contexts. These findings support the view that bridging the gap between academia and industry is not only a pedagogical challenge but also a question of cultivating students' epistemological agility, encouraging them to navigate and value both theoretical insight and applied innovation (Felder & Brent 2016, Graham 2018).

Navigating scientific and industrial literature

The second research question addressed students' ability to locate, interpret and apply scientific and industrial information. Reconstructing fabrication flows based on non-public industrial methods required students to independently identify relevant patents and research papers and integrate this information into their project reports. While a significant portion of students reported difficulties accessing and interpreting industrial sources, with 67% finding it "challenging" or "very challenging", the process was considered valuable for developing research skills. Most importantly, 71% of students reported becoming more critical of different information sources. Structured support, such as peer group discussions, weekly deadlines and access to tutors and lecturers, was key in scaffolding this skill. These findings indicate that, while demanding, the CBL environment effectively cultivated students' ability to independently identify, evaluate, and synthesise diverse information sources, a critical competency for both academic research and industrial practice. The results also highlight the crucial role of REP as a vehicle for managing and integrating complexity in advanced learners.

Interview data indicated that the need to understand unfamiliar terms and processes led students to engage more actively with the content, which they described as leading to learning that "sticks better". This aligns with prior studies noting that CBL can foster information literacy and research autonomy (Membrillo-Hernández et al. 2021, Clegg & Diller 2019). The project pushed students to operate in the space between formal academic content and the often less-structured, more pragmatic knowledge typical of industry contexts, thereby enhancing their ability to work across these epistemic domains.

Perceived benefits of the CBL approach

The third research question explored students' perceptions of the CBL model. Responses consistently highlighted the perceived benefits of the approach across multiple domains, despite initial feelings of overwhelm (reported by 36% at the beginning). As the course progressed and students became more familiar with the open-ended format, many reported increased confidence and a stronger sense of ownership of their learning. Students reported gains not only in content knowledge but also in skills such as communication, teamwork and self-management. Weekly feedback sessions, peer review of report drafts and ungraded presentations were particularly appreciated for supporting iterative learning and helping students build clarity and confidence in articulating their ideas.

These findings align with research on CBL's capacity to promote transferable skills and lifelong learning (Lazendic-Galloway et al. 2021, Höffken & Lazendic-Galloway 2024). While collaboration in this course was more informal than fully cooperative, peer discussion and feedback still played a central role in the learning process. Importantly, students also recognised the value of balancing open-ended project work with structured lecture-based learning and summative assessment. The distinction made by several students between the “deep, specific knowledge” gained from the project and the “broad conceptual understanding” reinforced through lectures and the exam reflects the dual purpose of a discipline-based CBL.

While CBL is often framed in the literature as an open-ended, project-driven approach that may replace traditional exams altogether (Gallagher & Savage 2020), our findings suggest that in conceptually dense and discipline-specific contexts such as physics, a hybrid approach may not only be beneficial but also necessary. Students clearly valued working on the challenge for its capacity to connect theory to industrial practice, foster deep engagement and develop research and communication skills. However, they also recognised the essential role of lectures and exams in grounding their understanding of complex theoretical concepts and procedural knowledge that underpin the discipline. This supports arguments from discipline-based education research that while active learning strategies can promote higher-order thinking, foundational knowledge in science and engineering must still be explicitly taught and assessed (National Research Council 2012, Wieman 2014).

In this course, the dual structure, combining a challenge-based project with a “traditional” exam-based component, created complementary pathways for achieving the intended learning outcomes. The project report and peer review enabled synthesis and application, whereas the exam ensured coverage of core concepts and analytical fluency. Several students articulated this synergy, noting that the assessment through the exam prepared them to think broadly across the field, while the project enabled them to think deeply within a specific topic. These findings resonate with Boud and Falchikov's (2006) call for integrative assessment approaches that not only measure content knowledge but also foster transferable skills and lifelong learning capabilities. Therefore, rather than viewing exam-like assessments as incompatible with CBL, this study suggests that well-designed assessments across multiple formats can support both disciplinary depth and professional relevance, an especially critical balance in advanced STEM education.

Broader pedagogical implications

The implementation of CBL in an advanced plasma physics course demonstrates the potential of this pedagogical approach to transform not only student engagement but also the structure and outcomes of science and engineering education. Several broader implications emerge from this study that may inform the design of similar courses in STEM disciplines.

First, the CBL model reinforces the value of *authentic, open-ended challenges* as a mechanism for deep learning. *Deep learning* here refers to the process where students aim to understand ideas for themselves, apply knowledge in different contexts, and make connections between concepts, as

opposed to *surface learning*, which involves rote memorisation for exams (Biggs, Kember & Leung 2001). Students describe engaging deeply with material because it was personally meaningful and required them to synthesise knowledge independently. They mention making connections between what was learned in lectures and how it applies in real-world contexts. The CBL format encouraged them to transfer theoretical knowledge to novel, authentic problems, which promotes flexible, transferable understanding. The uncertainty and ambiguity inherent in the project encouraged students to become active agents in their learning process, mirroring the complexity of real-world scientific and engineering problems. While this ambiguity initially overwhelmed some students, the structured scaffolding (weekly feedback loops, mentoring, and peer interactions) played a critical role in sustaining motivation and managing cognitive load. This suggests that, while CBL can be demanding, it is particularly effective when coupled with intentional instructional support.

Second, integrating diverse domains and synthesising information from academic, industrial and patent literature enabled students to break down the siloed nature of scientific education. This aligns with the increasing need for graduates who can work across disciplinary boundaries and navigate both scientific and technological domains. As seen in this course, exposing students to the type of informal reasoning and practical judgment required in industrial research settings can build transferable competencies that are often underdeveloped in more traditional academic curricula.

Third, the collaborative dynamic among students, tutors, and lecturers in this classroom model repositions educators as co-learners and facilitators. Students uncovered new sources and perspectives that even lecturers had not previously considered, emphasising the value of a more democratic, exploratory learning environment. This shift not only enriches the course content but also cultivates a lifelong learning mindset and mutual respect between students and faculty.

Furthermore, this study contributes to the growing body of research demonstrating that REP can be effective in highly specialised and theory-intensive domains. Our findings support the notion that REP can serve not only as a cognitive scaffold but also as a strategy for professional skill development, especially when direct industry collaboration is limited. By situating REP within a CBL framework, the course bridged disciplinary depth with real-world relevance, preparing students for work in technologically dynamic and confidential sectors such as nanoelectronics and advanced manufacturing.

Course changes based on this research

Insights gained from this study have led directly to modifications in the structure and assessment design of the plasma physics course. Based on student feedback, the survey and interview data, two major changes have been implemented to better align the course with its learning objectives and enhance the student experience.

First, the weight of the project component has been increased from 40% to 50% of the final grade. This adjustment reflects the central role the challenge-based project plays in promoting deep engagement, critical thinking, and the integration of theoretical and applied knowledge. It acknowledges that the project is not merely a supplementary activity but a core vehicle for learning in the course.

Second, the traditional written exam previously held at the end of the course has been replaced with two interim assessments in the first four weeks. These tests focus on foundational theoretical content and collectively account for the remaining 50% of the course grade. This change ensures that students acquire essential disciplinary knowledge early on, allowing them to devote the latter half of the course to the open-ended project without compromising conceptual rigour.

Together, these changes are designed to support a more balanced and integrated learning experience in which structured theoretical instruction and exploratory project work complement each other. This evolution in course design underscores the importance of aligning pedagogical innovation with ongoing feedback and evaluation, reinforcing CBL's potential to drive meaningful curricular transformation in advanced STEM education.

Conclusion

This study contributes to engineering education research by demonstrating how CBL can be effectively applied in a highly technical, concept-heavy domain such as plasma physics, even without direct industry involvement. It demonstrates that carefully scaffolded CBL projects not only supported deep disciplinary learning but also fostered transferable skills such as information literacy, problem-solving, and interdisciplinary thinking.

The course's hybrid structure, combining open-ended real-world challenges with traditional assessment (structured exams), offers a promising model for integrating CBL into advanced STEM curricula that balances conceptual rigour with professional relevance. Students actively constructed knowledge through exploration, peer collaboration and engagement with current practices, while structured support (e.g., weekly feedback, mentoring and peer review) helped them navigate uncertainty and stay motivated.

From the student perspective, the CBL approach was appreciated for its authenticity, its alignment with future career context, and the opportunity to apply theory in meaningful ways. Notably, activities such as reverse-engineering emerging technologies encouraged students to think critically about the fundamental concepts that underpin real-world innovations, further deepening their understanding. Most importantly, this study demonstrates that CBL can be adapted to fit within the learning objectives of concept-heavy disciplines such as physics.

Overall, this study underscores that while CBL demands careful scaffolding and careful instructional design, it is a powerful pedagogical framework (and concept) for cultivating both deep conceptual knowledge and the adaptive competencies students need in today's fast-evolving technological landscape. These findings offer practical insights for educators aiming to implement CBL in other advanced STEM contexts and highlight the importance of mirroring the complexity and ambiguity of the professional environments students will enter.

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Declaration of Interest

No conflict of interest.

Notes on Contributors

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