'Everything I love about physics' in a project-based undergrad lab course

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Abstract

We report on the development and implementation of P+, a novel project-based physics lab course. In this inquiry-based format, students choose their own topics, design and build the experimental setups, and conduct their own experiments. We discuss the pedagogical rationale behind P+, its implementation within the existing lab course format, and the challenges and successes encountered in the first two semesters of its conduction. We assess the skill development via a student survey, tracking their self-perceived skill levels associated with a set of learning goals. We find that all learning objectives are achieved in the new format at least to the same extent as in the standard laboratory course. Particularly positive effects are observed in the categories 'designing an experiment' and 'scientific communication'. In addition, students benefit from increased collaboration, a structured approach to project development, and the opportunity to explore their interests, which leads to exceptionally high motivation, a key factor for efficient learning.

Introduction

The primary goals of undergraduate physics laboratory courses at most universities are to equip students with the basic skills needed to conduct experiments, to familiarize them with laboratory equipment and procedures, and to strengthen their understanding of physics concepts taught in lectures (see e.g. Sokołowska & Michelini, 2018, chapter 5). While phenomenological experiments have long been the gold standard for introductory physics lab courses, there has been a growing emphasis in recent years on open-inquiry and project-based approaches. In 2022, in the aftermath of the COVID-19 pandemic, we set out to improve the physics laboratory curriculum at ETH Zurich through the development of a **P**roject-based **P**hysics **L**ab for **U**ndergraduate **S**tudents, P+ for short. The pandemic had necessitated a switch to remote lab classes, with students conducting self-built experiments at home. This experience revealed that certain skills were more effectively developed in this remote format compared to traditional laboratory settings due to the stronger involvement of the students in setting up an experiment. Based on this insight, motivated by the excitement about the Physics-At-Home experiments (Walther, 2022), and inspired by the success of the Projektlabor at the TU Berlin (Merli et al., 2020), in the spring semester of 2023 we conducted a pilot phase for an open-inquiry project-based lab class in which students choose the topics, develop and build the setups and carry our their own experiments. With funding from the Innovedum initiative at ETH Zurich in 2024 (ETH Zurich, 2024), we were able to expand and consolidate P+ as a sustainable alternative to the standard physics lab course. The new course found great resonance among the students as illustrated by the student testimony cited in the title of this paper. We report on the development and implementation of the novel format, describe the course structure and analyze the self-reported skill development of the P+ students in comparison to their colleagues in the traditional lab course.

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Implementation of P+

Learning goals

Inspired by our experiences with the 'at-home' experiments during the COVID-19 pandemic (Walther, 2022), we sought to implement a similar approach in our second-year undergraduate physics lab course at ETH Zurich. When embarking on the task of improving an existing course, the suitability of current and new course for teaching the desired learning objectives must also be quantified. We wanted to find out whether a project-based approach is as suitable or maybe even more efficient for teaching experimental skills. However, our main focus was on skills that cannot be taught, or only to a limited extent, in a traditional laboratory course. We defined a set of learning goals, leaning on the framework established by Zwickl et al. (2013). In this concept, the individual learning goals, e.g. 'oral presentation of scientific results' or 'ability to describe data in a compelling way', are sorted into four main categories - which would be 'scientific communication' in case of the examples given. A sketch is shown in Figure 1, and a list of all learning goals and their associated skills is provided in the appendix. Similar approaches to shift from guided-inquiry lab courses towards more open-inquiry experiments have been used at other universities, and an instructive description of such a transformation process can be found in Sokołowska & Michelini, 2018, chapter 8.

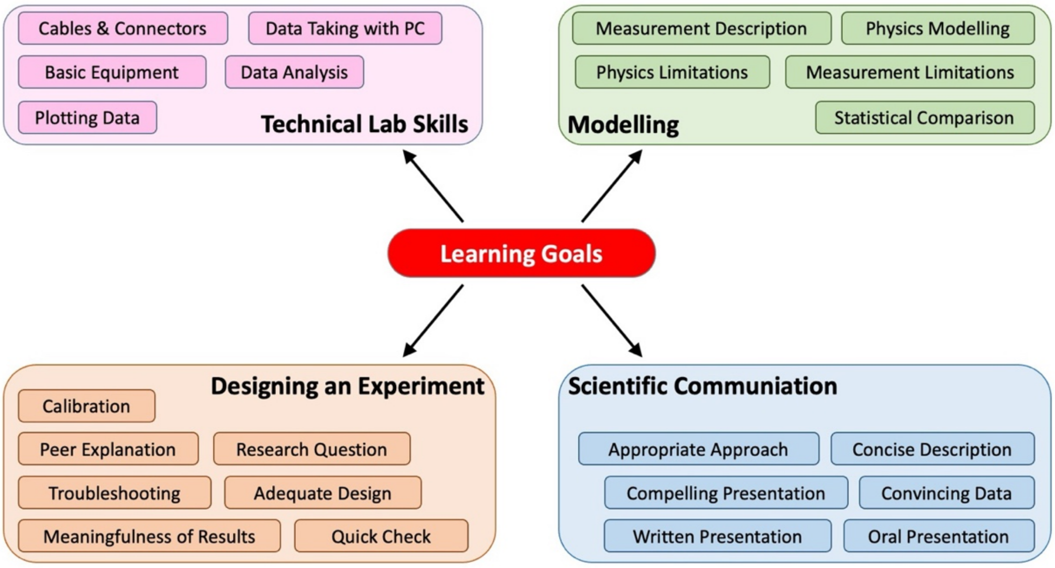

Figure 1: Overview of the learning goals and associated skills, sorted into four categories, leaning on the concept of Zwickl et al., 2013. Learning goals and the associated questions asked are listed in the appendix in Table A1.

It is clear that many of these learning goals are not addressed in the context of a traditional lab course. At ETH, the standard physics lab class is conducted in groups of two students during one half-day every week. The students work on readily available setups and perform a predefined sequence of experimental tasks. A teaching assistant who supervises the same experiment throughout the semester supports them if needed and takes care of correcting the reports. This means that students meet different teaching assistants each week, which increases the variety of inputs but at the same time does not allow for monitoring their progress over the semester. Several learning goals, such as designing and modeling, are not addressed when using given setups. Other skills, such as troubleshooting a setup, can only be trained within traditional courses if artificial hurdles are introduced. However, deliberately introduced bugs and problems in setups cannot provide an authentic learning experience. Finally, such transferable skills as planning and group collaboration can only be learnt while working on a full project, which is not possible in traditional lab courses. Therefore, we needed to change the existing organization of the lab courses quite fundamentally for P+, as described in the next section. This detailed and in part more technical description may also serve as a blueprint for similar endeavors.

Organizational structure of P+

At ETH, physics students visit the physics lab course in the second and third year of their Bachelor studies. After having absolved the ‘Basisjahr’, they first participate in the beginner’s lab classes called ‘P1’ and ‘P2’, followed by the advanced lab classes ‘P3’ and ‘P4’ (or an equivalent course, such as a semester project in a research group). The goal of P1 and P2 is to equip the students with the fundamentals of lab work, whereas P3 and P4 focus more on advanced physics and complex experimental setups. We introduced the project-based P+ with currently 36 places as an elective alternative to P2, i.e., after the students have completed their first semester of lab classes.

The structure for the standard lab course, as described briefly in the previous section, is unsuited for open-inquiry experiments. Because the students come with their own experimental ideas and need to think about and build a setup for their needs, every single experiment requires much more time for development. Execution of the experiment, the central part of traditional lab courses, is only the final step in P+. The variety and complexity of tasks until the experiment can be performed requires larger groups. In the P+, students work in groups of 6 and are accompanied by the same teaching assistants throughout the semester. In addition, the groups are supported by an advanced supervisor (the lecturer or an additional, advanced ‘head TA’, as explained in the next section). The very consistent support allows for close monitoring and steering of the individual’s and group's progress. It is also necessary for balancing the much greater freedom of the students, including the substantial risk of failure of a self-created experiment.

In the first week of the semester, a kick-off meeting between the group TAs and their students is scheduled. This helps strengthen the cohesion within the group and allows the students to get a feeling for the unfamiliar modes of working in a team and being responsible for their own goals. At this stage, the group also decides on the topics of the six experiments which they want to carry out in the coming months. The head TA or lecturer only intervens if necessary, e.g. to promote a more balanced selection of physics topics, or experimental and data analysis techniques.

From this point on, a clear organizational framework for the experiments is given, as shown in Figure 2, following a two-week cycle which is repeated six times throughout the semester. In the following, a sample schedule of such a two-week cycle is discussed.

Planning phase (week n):

In the first week of each cycle, the focus is on planning the experiment. Although students can organize themselves quite freely, there are two mandatory one-hour sessions. It is advisable not to schedule these on consecutive days, as a lot of researching, discussion, and plan refining is required between these sessions.

In ‘Tutorium 1’ (see Figure 2), students meet with the group TA to develop a first draft of their chosen experiment and its setup. It is important that students are guided at this early stage to structure their work well by identifying several goals and milestones of their experiment. Breaking down the overall goal into smaller steps has proven to be very important, as students tend to set their initial goal too high to be achievable in a realistic time frame. Another challenge the students face lies in the understanding of the physics underlying their experiment. This includes the typical application of a fundamental concept and equation to a concrete problem. However, they must also ensure all group members grasp the theoretical background. In the context of P+, they have the chance to have a guided (by the TA) but peer-centered discussion about physics.

The second mandatory preparation session, ‘Tutorium 2’, is dedicated to finalizing both the experimental plan and the details of the setup that needs to be built. The students discuss the specific measurements they will take, which results they expect, and how they will assemble the experiment in detail. By the start of the second session, students have the task of creating a list of the required equipment and materials. This allows TAs, the lecturer and technical staff to review their plan at this stage, ask clarifying questions and possibly suggest improvements to the setup. If the list of the desired material and equipment is in line with both the financial and time budget (of technical staff as well as students), the group will receive ‘green light’ and the equipment is organized, built (if possible, by the students), or purchased.

Execution phase (week n+1):

The second week is dedicated to executing the experiment. The third time slot (2.1, see Figure 2) is kept free of mandatory meetings, giving students time to work independently on their projects. Most groups use this slot to start building their setup, test some prototypes or perform preliminary measurements.

During the fourth time slot, the experiments are finally carried out. At the beginning of this half-day, all students participate in the ‘Vorsprache’, a set of short presentations that serve as an entry ticket to perform the experiment. Typically, three groups are scheduled together and present their final experimental plan to each other, explain the setup and provide a brief theoretical background. While the groups prepare the presentations together, typically using a whiteboard, only two randomly selected group members give the presentation. Most questions are asked by the other student groups but also the head TA or lecturer may ask questions and ultimately decides whether the students are prepared enough to be admitted to the experiment. Besides serving as quality assessment, the presentations also train students in scientific communication, a fundamental skill for scientists.

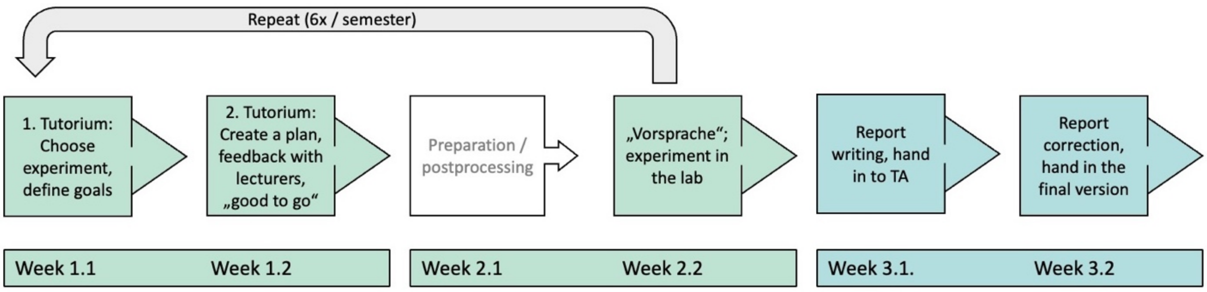

Figure 2: Two-week cycle of a P+ experiment, repeating 6 times per semester. Ideally, the slots with mandatory meetings are not on consecutive days, such that the students can progress on their tasks by themselves.

Once the ‘Vorsprache’ is successfully mastered, the students start to experiment. The official agreement is that they should carry out their experiment within the next four hours, reaching at least a certain step of the experimental plan, which is agreed upon in the planning phase. This will suffice for passing the experiment. In many cases, however, it turned out that the students and their group TAs were motivated to push further and stayed much longer. From the lecturer’s side it is important to stress that staying (significantly) longer is not expected and promoted. But as a student explained, ‘we could have gone home after reaching the first mile-stone, but we just really, really wanted to reach the next level’.

Upon completion of the experiment, a scientific report has to be written within one week. In each cycle, two students are assigned to be main responsible authors, while the other group members support them. The report is submitted to the group TA and later to the head TA for corrections and iterated in a peer-review manner until its acceptance.

Students supervising students with an advanced teaching assistant supporting in the background

The P+ pilot project in 2023 had already received a very positive resonance among the stu-dents and had been overbooked by a factor of two (18 student slots for 36 subscribed stu-dents). To expand the capacities, we adapted our supervision structure by including another supervision layer. The pilot phase of P+ had highlighted the importance of effective teaching assistant (TA) supervision for student learning in this project-based approach. For the first round of P+, two of the authors and another experienced and extremely motivated TA served as group TAs. The initial supervision structure is depicted in Figure 3a).

It was clear for us that especially the role of the lecturer was not scalable, who was heavily involved in checking the feasibility of the experiment per se, as well as the experimental setup. In addition, the tasks of providing technical support and executing quality control (this includes the quality of the research questions, sufficient preparation of the students, the quality of the report, but also the safety of the experimental setup) consumed a significant amount of time. The teaching assistants, on the other hand, were well occupied with guiding the students through the development process of their experiment, supporting them in theoretical and experimental difficulties, and dealing with group dynamics. While the teaching assistants, who were quite experienced themselves, could have taken over a large part of the quality control, they did not have time in this supervisory structure, and it would also have led to role conflicts, since they would then have been both the 'best friend' and the controlling authority of the group.

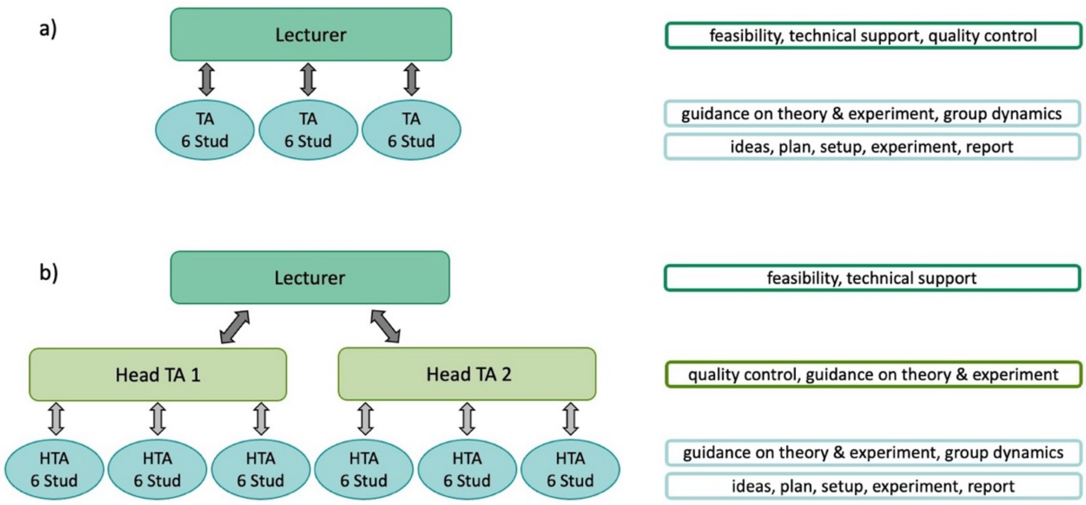

Figure 3: Structure of the supervision a) in the pilot year 2023 and b) in 2024, where budget was available to hire student teaching assistants (HTAs) and use regular TAs as additional supervision layer. The main tasks and responsibilities are listed on the right-hand side.

In order to upscale the P+ capacity and make the concept more sustainable in terms of teaching hours and preparation time, for the second round we implemented an additional layer of supervision by adding the role of head TAs and introducing student teaching assistants (HTAs) as group TAs. This significantly reduced the lecturer's workload, because the quality control as well as part of the feasibility considerations could now be delegated to the head TAs. This structure is sketched in Figure 3b). Every head TA is responsible for 3 groups, each group is accompanied by one HTA. The head TAs, having a broader experience and knowledge in experimental physics, can advise the groups already in an early stage regarding experiment construction, and assist the lecturer by sorting out unfeasible experiment ideas at an early stage. The group (H)TAs in turn are close to their respective groups and can contribute well to a constructive and supportive group atmosphere.

With the introduction of HTAs as group TAs, the capacity of P+ could be doubled from 2023 to 2024: 36 instead of 18 students in P+, corresponding to 18 students per head TA. We could directly recruit the HTAs from the veterans of the P+ pilot and finance their salary by an Innovedum grant (ETH Zurich, 2024), which also gave us the opportunity to purchase further equipment and tools, such as a 3D printer, for the P+ students. In the perception of the students, the HTAs, due to their recent undergraduate experience, felt more approachable, which encouraged the students to ask questions more readily. The HTAs were found to be extremely motivated, spirited, and involved and in many cases served as an additional driver for their groups. This factor, on the other hand, possibly influenced the students' invested time into P+, which increased from 2023 to 2024, as further discussed below.

Results from the students' survey

Quantifying the effectiveness of P+ to achieve the set learning goals, even in relation to the traditional P2 laboratory course, presents several challenges. First, at ETH Zurich, neither P+ nor P2 have a formal performance assessment (e.g., exams or grading of the reports) which could be compared. Second, the immense variety of the projects within P+ makes a straightforward comparison of student skill acquisition nearly impossible. How, for example, can one objectively compare the development of a cloud chamber with particle trail analysis using AI algorithms against the construction of a Stirling engine? Finally, the small group of students in P+ during the past two academic years makes any statistically significant quantifications difficult, a fact that should be kept in mind when considering our results.

Nevertheless, attempting to evaluate whether our changes were effective, we carried out a student survey. The questionnaire included a self-assessment of 23 distinct skills corresponding to the learning goals defined in Figure 1 and a second part with a general evaluation of P+. The survey was completed twice by the students; once before and once after the semester. A unique anonymous six-digit identifier allowed comparing pre- and post-course feedback.

As in both years the demand for P+ was a factor of two higher than the capacity, we could include all students who applied for P+ into the survey, and use those students as a test group who didn't get a spot in P+ and thus carried out the standard course P2. Given that the students all had applied for P+, we assumed that there would initially be no significant difference between them. Comparing students who are interested in participating in a novel and project-based lab course with those who avoid it, might, however, produce an inherent bias. The exclusion of all students who did not apply for P+ contributed to an overall small number of returned questionnaires: In total, pair-wise analysis could be performed for 11 students in P2 and 35 students in P+.

In the first part of the questionnaire, the students were asked to rate their own skill levels in the categories discussed above on a scale from 0 to 10, with 0 indicating 'no skill' or 'no experience', and 10 indicating 'expert skill' or 'expert experience'. Figure 4 shows spider diagrams of the self-assessed skill levels in two main categories, 'technical lab skills' and 'designing an experiment'. In Figure 4a), the 5 skills connected to 'technical lab skills' are displayed. The shaded grey area in the center represents the skill levels before they visited the physics lab (called 'pre-lab'). The solid blue line represents the self-assessed skill level of students after completing P2, and the solid orange line of those completing P+. The similar curves indicate that in the category 'technical lab skills', the students perceive an increase of their technical lab skills in either lab course format by an almost equal amount.

As a general finding, for every learning goal we found that within the framework of P+, at least about the same perceived skill levels were reached as compared to the traditional lab course (Figure 4a represents the 'worst result' for P+ in that regard). In several categories, P+ students rated their skills after the semester much higher than the P2 test group. One example for such a much higher rated category is given in Figure 4b): In 'designing an experiment', P+ students felt much more competent.

In Figure 5, we show the average perceived increase in skill level for all 23 learning goals. This value is calculated as the difference between the rated skill level after and before visiting P+/P2 for every student individually, and then averaged over all P+ and P2 students, respectively. Here we see again that the P+ students rate the increase of their own skill level at least as high as the P2 students do, while in many categories the perceived competencies have improved much more within the new format.

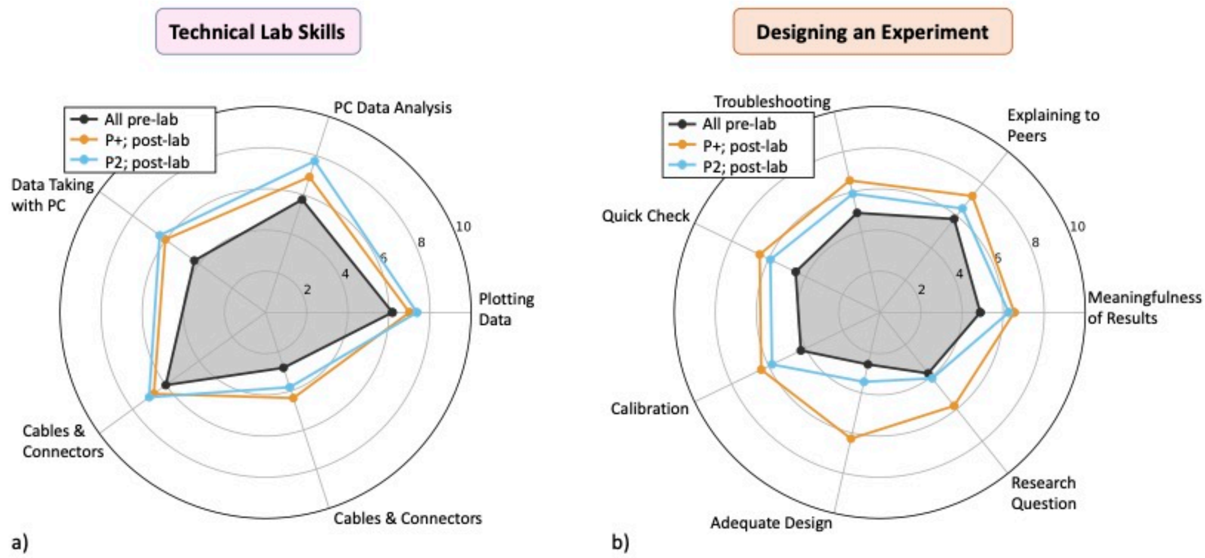

Figure 4: Spider diagrams of the perceived increase in competence by the students, where the skill levels before ('pre-lab') and after ('post-lab') completing the more standard P2 and the novel course, P+, respectively, are compared. Shown are the averaged data for the 5 skills from a) the main category 'technical lab skills' and b) for the 7 skills of the category 'designing an experiment'.

In the second part of our questionnaire, we posed more general questions about their experience with the P+. The answers overall were very positive and enthusiastic. When we asked: 'on a scale from 1 (=never) to 10 (=by any means), would you do P+ again?', twelve out of twenty students answered with a 9 or 10, and only four students answered with a 4 or 5, the lowest marks given. Another very strong example for the good reception of the P+ was the inquiry whether they could imagine becoming an HTA for the P+ in the coming semesters. Fourteen out of twenty answered with 'yes', while three were undecided and four said 'no'. The most frequent answer to our open question about what the P+ had taught them in addition to the above asked skills was 'team management', followed by related competencies, such as conflict, time or resources management.

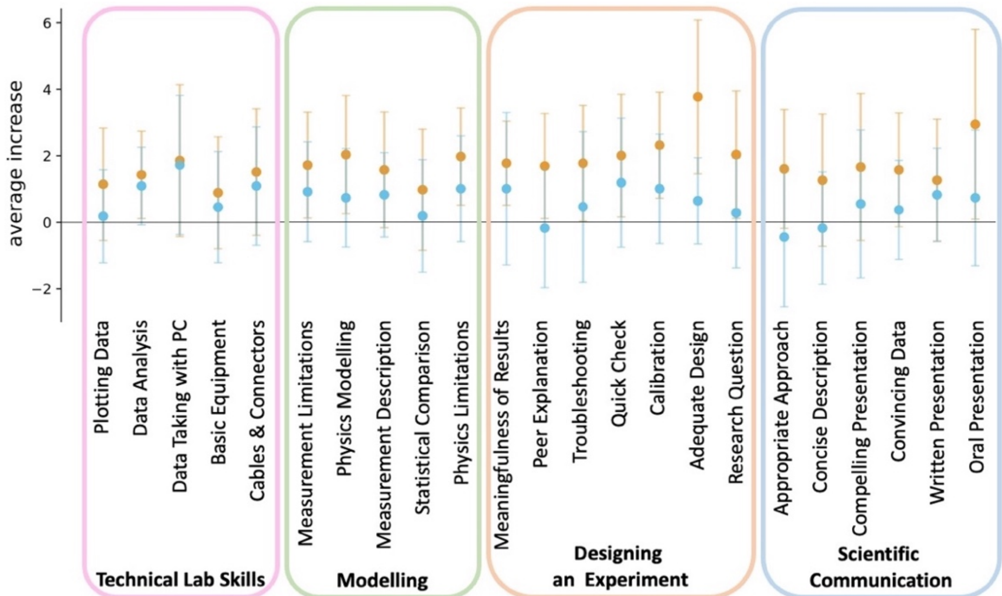

Figure 5: The relative increase for all 23 skills (corresponding to the learning goals as defined in Figure 1 is shown as reported by the students in P2 (blue) and P+ (orange).

Last but not least, we asked the students how many hours they invested in the physics lab course. Students receive 6 ECTS credits for P2 or P+, which corresponds to a nominal workload of 180 hours. In our experience, the P2 takes about 100 hours. In the pilot phase of P+ in 2023, students reported an average time investment of 120 hours, with 2 students working 180 or more hours, and 5 students working 100 or less hours. In the consolidation phase in 2024, the reported average increased to 151 hours. The extensive time spent for P+ was one of the main points of criticism coming from the students. Other students said that the experiments felt 'a bit rushed'. Thus, in future development of P+ we will try to balance the allotted time for the experiments better, as further discussed below.

We want to conclude this section with two student testimonies that stand for all the valuable feedback we received that motivates us to further invest in and develop P+ in the years to come:

- 'I learned how to discuss experiment ideas, distribute tasks and discharge unrealistic ideas. I communicated a lot with my HTA but also with [the lecturer and head TAs]. It was by far the most contact I ever had with teaching people at ETH. In general, the experience was incredibly diverse, the learning process was much more multilayered than in P1 and to me the work felt like the most meaningful for my formation during my studies at ETH so far.'
- 'It will cost you a lot of time. But P+ is everything what I love about Physics, and to be able to experience it while in the second year of physics is phenomenal.'

Discussion

The positive student feedback and the improved perceived skill levels were a very satisfying outcome for us, but the question is valid: Do these data also reflect the students' learning? While acknowledging the limitations of self-assessed data, research (Deslauriers et al., 2019) has shown that self-assessed skill levels can be a reliable and instructive measure for the efficiency and efficacy of a new course. The study even indicates that perceived competencies tend to be rated lower by students taking part in an active learning format as compared to traditional formats, while they ultimately score better in formal assessments.

In our survey, the overall increase of perceived skill levels is observable and substantial. Especially in 'scientific communication' and 'designing an experiment' it appears that the learning goals can be achieved better in the project-based lab format. It is also easy to understand that some learning goals are only addressed in one course format and some are almost mutually exclusive. For example, teaching students a lot of experiment design and letting them invent setups by themselves will obviously not improve the skills in categories such as 'knowing cables and connectors' equally well as for a guided-inquiry classical lab experiment.

A defining characteristic of the P+ students was their exceptional motivation. They show great motivation to understand complex physics phenomena and often exceed expectations in terms of time commitment and effort. A student's response to Nobel Laureate Carl Wieman during a visit of P+ in May 2024 serves as a striking example of this strong motivation: When asked about their higher time investment compared to their colleagues in the traditional P2 course, she replied: 'Yes, but we also learn much more than they [students in P2]! We have here the opportunity to do real physics, and of course we could stop after reaching our first milestone, but we want to reach the next milestone as well!'.

As underlined by Self-Determination Theory (SDT) (Ryan & Deci, 2020), intrinsic motivation is a cornerstone of effective learning. We firmly believe that the autonomy given to the students in the P+ fosters their motivation and thus a positive learning environment. Research in the context of SDT showed that intrinsic motivation also leads to greater identification of undergrad students with being scientists (Skinner et al., 2017). This identification is known to be key for the success of students, with particular impact on students from underrepresented groups, namely women in STEM, first-generation university students, and other minorities. In P+, it is further fostered by the strong sense of belonging to their group and the experience of competence that clearly emerges from our survey. For us, these facets of P+ are of utmost importance.

Taking into account the students' criticism and suggestions for improvement, we plan to further optimize time management within P+, balancing the time invested by the students and the variety of topics, while at the same time maintaining the students' autonomy, as is is directly linked to their motivation.

One possible solution that takes both the ‘rushed feeling’ and the high load into account is to reduce the number of experiments during a semester and increase the allocated time for them. However, this could have the disadvantage of limiting the range of topics covered too much. Further, six experiments have the added benefit that each student can select a topic. In principle, by introducing experimental milestones, the students already have the possibility to complete their experiments within a reasonable time frame, and we recognize the importance of student motivation and appreciate their desire to ‘push through’ challenging projects. For us, the rewarding experience of leaving the laboratory tired but satisfied due to a successful experimental result is a beloved part of being an experimental scientist. But staying longer in the lab may not be fully by choice, it is possible that some students feel peer pressure. We will alert the group TAs and the supervising TAs to these possible dynamics and ask for clear communication when the ‘sufficient’ level of the experiment has been reached. Further, to avoid the frustration of failure, each group can at their own request drop one of the planned experiments every semester in order to continue with the current experiment in the following cycle and optimize it. This also allows them to train optimization processes, and they can achieve satisfactory success in the end.

In addition, we will try a simple but hopefully effective measure to let students make better use of the allotted experiment time. We will introduce ‘Experiment Zero’ as a module at the beginning of the semester in which important experimental techniques and skills are taught. The groups are split up, each member visiting one of six stations that focus on a specific topic (e.g. ‘temperature and pressure measurements’ or ‘3D printing’). Afterwards, students return to their groups as experts in their topic. We hope that this activity will foster efficient teamwork within and collaboration between groups. It will certainly help to avoid time-consuming experimental challenges, which we have observed frequently.

Conclusion

With the introduction of P+, we have created a valuable alternative to the traditional physics lab course, from which a significant proportion of students benefit greatly. The P+ paves the transition from guided, structured projects to open, self-managed group work. The high level of student motivation, reflected for example in the student testimony cited in the title of this work, demonstrates their appreciation for this new lab course format. We have observed improvements in students' skills across various areas which are important for their future work as scientists in research groups.

While project-based open-inquiry group work may not be ideal for all students, the insights gained from the P+ experiments have convinced us to also introduce some of the concepts in the traditional lab course P2. For example, we plan to adapt the supervision structure to one teaching assistant staying with a group of students for the whole semester. Further, the number of written reports will be reduced while increasing the depth and quality of those that remain.
Finally, we would like to comment on the broader applicability of our layered supervision system leaning on HTAs. One extremely positive aspect of P+ emerging from many discussions is that the HTAs benefited significantly from their experiences as group supervisors. Many expressed that their own physics knowledge and experimental skills improved even more than when being P+ students. Recruiting highly motivated HTAs as an option to partially alleviate the increasing need for teaching assistants across ETH therefore appears to be a win-win-win-win situation: for the students, the student TAs, for us in our role as teachers, and for the mission to provide high-quality teaching in the face of steadily growing student numbers.

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Appendix

Technical Lab Skills	Plotting Data	How would you rate your skills in plotting data in-situ for a rough, first approximation of a result?
	Data Analysis	How experienced are you in performing computer-aided data analysis?
	Data Taking with PC	How experienced are you with computer-aided data taking?
	Basic Equipment	How confident do you feel with handling basic lab equipment such as calliper, multimeter, oscilloscope etc?
	Cables & Connectors	How familiar are you with different cable types and connectors (e.g. BNC, LEMO, coaxial cables, shielded cables, ...)
Modeling	Measurement Limitations	How do you rate your ability to determine and formulate the limits of a measurement model? I.e. can you explain where your setup has shortcomings and which parts of the physics is neglected/ignored?
	Physics Modeling	How well can you develop a predictive model to describe the physics you want to investigate?
	Measurement Description	How well can you model and desribe a measurement system? I.e. how experienced are you in predicting what an input quantity for a measurement device is (e.g. CCD-camera), what is its output, and what happens in the device?
	Statistical Comparison	How experienced are you with statistical comparison between data and theory/model? (i.e. data fitting, indication of goodness of fit etc.)
	Physics Limitations	How do you estimate your experience in articulating limits of a physics model? How experienced are you in arguing up to which point your physics model can describe a phenomenon correctly, and where its limitations are?
Designing an Experiment	Meaningfulness of Results	How experienced are you with judging the meaningfulness of your results? Can you perform a plausibility check instantaneoulsy?
	Peer Explanation	How well can you explain an average physics lab experiment to your colleagues? This includes the underlying physics, the setup, measurement devices, expected results and the interpretation of measured data.
	Troubleshooting	How do you rate your skills in troubleshooting a setup and finding mistakes when something does not work in the lab?
	Quick Check	How do you rate your skills in quickly checking a setup and verifying that all components work as they should? (compared to the quesiton above, this is usually done before the measurement is started)
	Calibration	How experienced are you with calibrating a setup?
	Adequate Design	How do you rate your skills in designing an experiment in a clever and efficient way, and how well can justify why this design is the most appropriate?
	Research Question	Every setup is designed based on a well-defined, testable research question. How well can you specify independent, dependent and control variables in a setup?

Scientific Communi-cation	Appropriate Approach	How do you rate your skills in defending a chosen approach to measure a quantity, when you have to compare it to other ways of measuring the same quantity?
	Concise Description	How do you rate your skills in describing an experimental setup in a concise, scientific way?
	Compelling Presentation	How do you rate your experience in presenting data in a compelling way, which also non-experts in this particular field find easy to interpret?
	Convincing Data	How experienced are you with reasoning why your data is convincing? This includes that you have to account for possible short comings of the setup, and why their influence is (hopefully) of minor importance.
	Written Presentation	How do you rate your skills in writing a scientific report presenting your experiment (theory, model, setup and data analysis)?
	Oral Presen-tation	How do you rate your skills in presenting and defending a setup and obtained results orally? This can be in front of peers (e.g. Vorsprache in P+), a teaching assistant, or any other knowledgeable but non-expert audience.

Table A1: List of questions asked in the questionnaire.