Differences and similarities in approaches to physics LAB-courses

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Many universities attempt through their lab courses to teach students how to successfully engage in physics inquiry. It is known that doing so effectively requires students to participate in genuine inquiry: Learning to *do science* by doing science. Still, many different approaches can be envisioned. Should students always pose their own research questions, or should we gradually allow them more freedom? What minimum knowledge is required before they can reason with scientific evidence effectively and how do they acquire this knowledge in a meaningful way? How much time should be devoted to teaching students how to communicate their results in different formats, and how can we improve the quality of their writing? And, if we succeed in designing a course with which this broad goal can be attained, what is the workload for both students and teachers? What tools do we have to evaluate whether students master the knowledge, skills and competences that allows them to participate in more complex and independent physics inquiries in later years?

In this symposium, we compare the approaches to physics LAB-courses of four universities: University of Colorado Boulder (UCB), Amsterdam University College (AUC), Leiden University (LU) & Delft University of Technology (DUT). Each presenter will provide an outline of the approach and the rationale for it. One of the experiments or activities that is representative for the specific course will be highlighted.

Once the different labcourses have been outlined, we will discuss their similarities and differences more deeply, with specific attention to difficulties encountered and overcome. The questions and topics addressed above will be the point of departure for an engaging discussion.

Introducing students to physics inquiry at Delft University of Technology

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Abstract. We introduce approximately 300 students per year to physics inquiry in the first year physics lab course at Delft University of Technology. The course comprises 168h hours, divided over four octals, each with a different educational focus. The course has been structured using the Procedural and Conceptual Knowledge in Science (PACKS) model. We present the applicability of the model, the rationale of this approach, and an example of one of the experiments in the course.

1 Introduction and course structure

At the applied physics bachelor program of Delft University of Technology (DUT) approximately 300 students start each year. In the first two semesters, all students engage in the first year physics lab course (FYPLC). The main goal of this ~168h course is to develop in students the inquiry skills and understandings that allow them to do more complex and independent research in later on years.

The outline of the course is given in Table 1. In the FYPLC we distinguish three phases, where the first comprises two out of four octals (period of four weeks). In the *introduction phase* the focus is on the basic principles of setting up a method, gathering, processing and presenting data (in Python). Seven self-explanatory Jupyter Notebooks are made to get students acquainted with Python, data- and error-analysis. Students apply the acquired knowledge in an introductory experiment in which they determine the relation between the force between two magnets and their mutual distance. In the second experiment we put their knowledge to the test by having them determine the fourth digit of the acceleration due to gravity, and to be within 0.1% accuracy of the literature value.

Table 1 The outline of the FYPLC

Phase	Content	hours	Assessment	PACKS knowledge type
Introduction	Programming and data-analysis in python	40	Test	B & D
	Experiment 1: The relation between force and distance of two magnets	24	Results & conclusion	A & D
	Experiment 2: Determining *g* with an accuracy of 0.1%.	12	Abstract	D
Practice	Determining the Boltzmann constant using the (V,I)-characteristic of a diode using digital multi meters	12	Paper	C
	Determining RC-characteristics using an oscilloscope	8	Digital labjournal	C
	Determining the spectral lines of Na or Hg using spectroscopy	12	Report	C
Application	Self-conceived experiment	40	Paper	A-D

In the *practice phase* the focus is on getting familiar with frequently used equipment and measurement techniques. Students carry out three 'recipe-style' experiments. These experiments familiarizes them with spectroscopy and electronics circuits and measurement methods.

In the *application phase* students apply their acquired knowledge by planning their own inquiry. Students first pick from a list a topic of their interest. A small theoretical introduction and an experimental setup is provided. Students then pose their own research question and conceive their own experiment.

2 Rationales for the course outline

The FYPLC has been renewed in 2020. The *Procedural and Conceptual Knowledge in Science* (PACKS) model [1] has been used as a way to structure the course and make pedagogical decisions. The model, presented in Figure 1, links the various types of knowledge and their influence in each step of a scientific inquiry. As carrying out the inquiry with unfamiliar, complicated equipment (knowledge type **C**), without a proper understanding of what has to be done (**A**), simultaneously studying, describing and explaining a phenomenon (**B**) whilst keeping up the scientific standards (**D**) may easily distract students from focussing on and attaining the main goal, we aim per activity at a specific knowledge type. For instance, when determining the fourth significant figure of *g*, students understand the (purpose of the) task, are familiar with the conceptual content involved, and know how to operate the instruments. This allows them to focus on knowledge type **D**, devising a method that yield highly accurate data. As in real physics inquiries different types of knowledge are often applied in an integrated way where they interfere with each other [2], students devise their own inquiries in the application phase where they devise their own experiment.

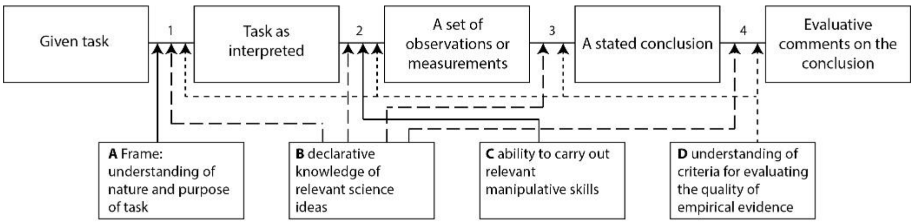

Figure 1. The PACKS model links the various types of knowledge and their influence in each step of an inquiry. In the renewal of the course, the model has been used to guide pedagogical decisions.

3 Ensuing challenges

Students keep on struggling with writing a concise but clear report. We now explore how peer review can be used as it might provide them examples of good reports, and have them develop a feel for quality.

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Engaging students in experimental modeling through an electronics lab course

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Abstract. The third-year Electronics for Physical Sciences course at the University of Colorado focuses on mostly analog electronics with 10 guided labs and a five-week student designed project phase. One of the key learning objectives is for students to develop proficiency with modeling, which entails constructing, testing, and refining models of both the physical system under study as well as the measurement system. We will present the modeling framework, how it is integrated into the course, and some outcomes of student learning, including identified student challenges.

1 Introduction

Several years ago, we engaged in a systematic overhaul of the third-year Electronics for the Physical Sciences course (PHYS 3330) [1-3]. Several ideas were used to guide the changes. These ideas arose from structured discussions with a faculty members in the context of creating learning goals for the Advanced Lab, the subsequent transformation work conducted in the Advanced Laboratory course, our experience teaching the PHYS 3330 many times, and our experience with electronics in a research-lab setting. The goals that guided the transformation included:

(1) making the experience more authentic and align with current practices of experimentalists working with electronics, [addressing calls from researchers and national studies in higher education]
(2) reducing the coursework overload on students, and having it more adequately reflect a 2-credit laboratory workload,
(3) including design and application activities in the guided-lab portion of the course,
(4) to better prepare the students for their projects and make them more accountable during this portion of the course.

The outcome objectives for students included:

(a) developing student expertise with key measurement and design equipment (oscilloscopes, boards, multimeters, programming, etc.) along with data collection and measurement techniques
(b) characterizing, modeling, and understanding applications of key core components (discrete components R,L,C, voltage dividers, operational amplifiers, transistors, etc.)
(c) developing capacity for theoretical modeling of foundational circuits & comparing theory to experimental measurement
(d) increasing student satisfaction and engagement.

2 Modeling framework for experimental physics

Having students develop proficiency with modeling was a key goal and was guided by the Experimental Modeling Framework (EMF), displayed in Figure 2 [4]. The EMF is one way to describe the nonlinear, recursive process through which experimental physicists develop, use, and refine models and apparatus. In the context of upper-division physics lab courses, we developed the EMF to characterize students' model-based reasoning and to inform the development of instructional lab environments that engage students in the practice of modelling. Modeling is the process through which models and systems are brought into better agreement, either by refining the model or the target system itself. The EMF divides the target system into two parts, each with its own corresponding model: the physical system and the measurement system. This division reflects the fact that experimental physicists often operate measurement equipment in regimes where the limitations of that equipment become important.

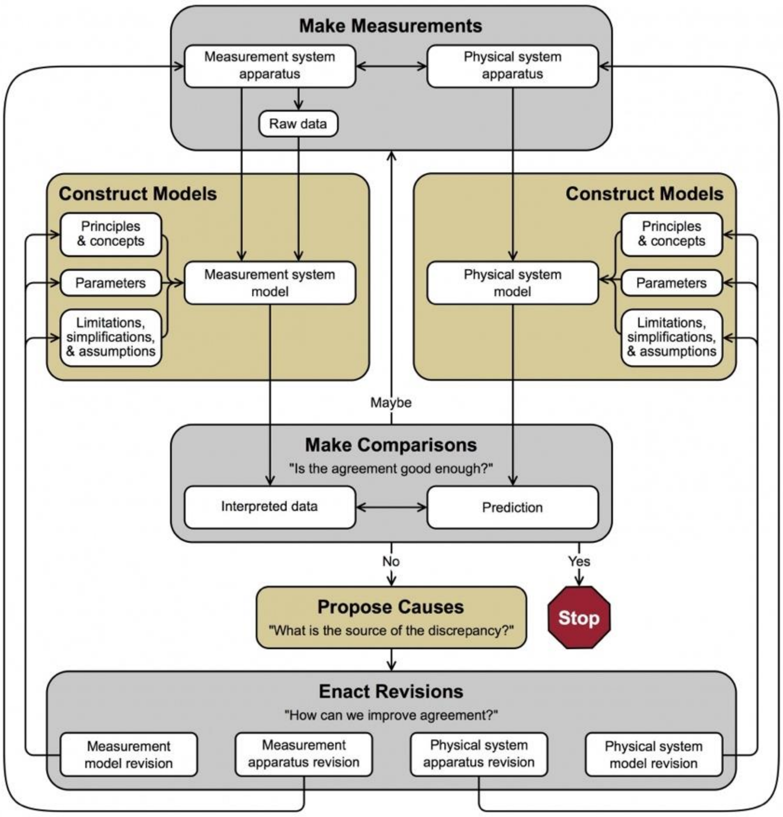

Figure 2. Modeling Framework for Experimental Physics [4]

3 Ensuing challenges

One of the remaining challenges is that students struggle with deciding what is "good enough" and when to stop the iterative modeling process.

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Engaging students in second year lab courses

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Abstract. During their second year, about 50 physics students engage in an open inquiry lab course of 56h that prepares them for their bachelor research project. Two combined theory-practical courses (of which 84h are spent in the lab) precede this open inquiry course and focus on among others the Fourier transform and signal processing. Courses that focus on specific research skills are based on Holmes' SQI-model and the latter course that focuses on general research skills is based on Etkina's ISLE-model. We have found that quantitative physics research as opposed to focusing on certain skills is needed to engage the students effectively.

1 Introduction and course structure

Each year, about 50 students start their second year at the physics bachelor at Leiden university. In the second year there are two combined theory-practical courses (PE1&2) followed by one open inquiry course (PE3), see Table 2. PE1 focuses on the Fourier transform (FT), PE2 on signal processing, noise reduction, and feedback systems. These courses culminate in a final open inquiry lab course (PE3) in which the students are free to conceive their own research project as long as it contains aspects of every part of the content of PE1 & PE2.

Table 2 The outline of the second year physics lab courses

Course	Topics	Assessment	SQI/ISLE
PE1 Total 84h Lab 42h	FT and magnitude and phase of transfer functions	Preparation & Lab journal	SQI
	Four experiments on data acquisition are finalized in a choice of three experiments out of six		
	Reading and writing using the NI MyDAQ, and FFT		
PE2 Total 140h Lab 42h	Step and impulse response (2 options) and 2D FT (2 options) Noise characterization (3 options) and reduction (2 options) Feedback (thermal or optical) systems (2 options) OpAmps (7 options)	Preparation & Lab journal	SQI
PE3 Lab 56h	Open inquiry on signal processing, noise reduction and feedback systems	Proposal & Paper	ISLE
	Students first design and test their own setup and subsequently optimize it to do physics research		

The main goal of all physics lab courses is to develop students' general research skills, together with more specific research (apparatus & analytical) skills and the development of understanding the place of, and the need for theory in physics research. This way, students are being prepared for their 672h bachelor research project at the end of their third year.

We distinguish experiments in which the main research question is given together with some underlying theory (both physics and analysis theory) and some information on the apparatus to be used (PE1&2), from the more open experiments in which students come up with their own research question within a certain (broad) field of physics (PE3). The open experiments are preceded by experiments that focus on learning how to use certain theory, apparatus, and analytical skills – necessary to answer given research questions [1].

These specific skills are taught within the frame of a full physics research cycle. We structure such experiments according to Holmes' Structured Quantitative Inquiry Labs (SQI) [2]. Special in SQI labs is that some form of repetition is needed, e.g. a second research cycle with a more elaborate research question, in a different context, or to improve precision, etc. We motivate the students extra by giving them choices from a list with various options [4].

The open inquiry experiments focus on general research skills. These experiments are structured according to Etkina's Investigative Science Learning Environment (ISLE) [3]. In these ISLE labs there is a natural need for repetition while completing multiple research cycles. These experiments are 'only' limited by our students' imagination and creativity and perhaps a subject to which we confine their research.

2 Rationales for the course outline

The physics lab courses have been continuously renewed from 2017 onward. Learning objectives have always been our starting point and are closely connected to the Dublin descriptors [5]. Last year, based on students' evaluations, we included research questions that challenges students to seek the limitations of using the NI MyDAQ rather than teaching them reading and writing data using this data-acquisition board only for future use.

Similar solutions were implemented for all parts of PE1 & PE2. We created challenging research questions in which the need for the various learning objectives would be apparent to the students. For PE3 we moved away from design research – feedback systems, signal processing, and noise reduction naturally call for this type of research – by requiring students to investigate some quantitative relationship. Students still use their newly developed design skills but now it is almost always intended to optimize a setup that is to be used to do quantitative research with. This changed the mood of the course completely.

Students enjoyed these changes and their appreciation for the preparing combined theory-practical SQI-courses grew. And where their appreciation for the open inquiry course was already high it still went up making it the highest appreciated lab course in the physics bachelor programme and one of the most appreciated courses for the physics bachelor as well.

3 Ensuing challenges

Students struggle with preparing their lab work sufficiently, especially the data analysis and error propagation parts. Peer review helps somewhat but not enough. In this respect, a newly developed rubric should steer the students better in the right direction. Furthermore, the students' work load is quite high.

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Maker Lab: a radically open physical science lab course for multi-disciplinary cohorts of natural science students

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Abstract. The Maker Lab course at the Amsterdam University College is designed to support students in doing experimental science by leveraging the accessible tools of the Maker movement. The Maker Lab apportions (56h) workload to training research skills before giving pairs of students full agency in conceiving, designing, and carrying out two of their own scientific inquiries (56h each). The structure for supporting student open inquiries, some observations, and one continuing challenge will be presented.

1 Introduction and course structure

Amsterdam University College's (AUC) Maker Lab course (168h) was developed and first given in spring 2020 as the product of a Comenius Teaching fellowship from the Netherlands Initiative for Education Research and the Dutch Ministry for Education. The course – open to all upperclass students who passed university calculus - spreads across a 15 week semester and is cross-listed between AUC's physics and information sciences tracks. AUC students build their own curricula, requiring the Maker Lab course to attract enough students who either choose it as their science lab requirement or take it as an elective.

The course's partially overlapping goals include:

- Train the skills in critical thinking and reflection needed in scientific research
- Increase student self-efficacy and motivation for doing experimental physical science
- Obtain a realistic image of the scientific process
- Attract and serve multi-disciplinary cohorts of natural science BSc students in AUC's liberal arts and sciences program

As the name implies, the Maker Lab utilizes Maker tools for scientific purposes. Students are taught to use Arduino Uno's to control various kinds of modern electronic sensors made cheap and accessible by the Maker movement. After introductions to experimental design and statistical and uncertainty analysis using Python, the initial 5 week skills-building phase of the course hands off responsibility to students, where they gain full agency in the empirical research process. In pairs, students conceive, design, and carry out two subsequent 5 week open inquiries. Besides the time limit, the only constraints on their projects are the use of self-programmed microcontrollers for data collection and the requirement that topics involve science concepts and/or mathematical modelling which go beyond high school material. While students have full epistemic and decision-making agencies in choosing their topics and research methods, the open inquiry phases are carefully regimented, as shown in Table 3.

Table 3's columns with contact hours also demonstrate the flipped nature of the Maker Lab: Relatively few synchronous class sessions are supplemented by frequent 30 minute meetings between inquiry teams and the instructor. The students build up and carry out their experiments unsupervised at home or in the out-of-doors. The team-instructor meetings, depending on the phase of the project and the students' current questions, take place either in-person or via video call.

Table 3. Course outline for Maker Lab 2022, not including a guest lecture and an excursion to a Maker space

Phase	Content	Class sessions (contact hours)	Meeting *N* teams (contact hours)	Assessment (graded work in bold-case)
Skills training	Basic data acquisition with and programming of microcontrollers	3	-	**Digital signals and Arduino exercise in Tinkercad**
	Programming, data-analysis, statistical inference, and uncertainty propagation in Python	3	-	**Statistical analysis and uncertainty propagation exercise in Jupyter Notebooks**
	Experimental design: five ways of determining "*g*"	4.5	2x0.5x*N*	**Presentations on semi-structured experiments**
First Open Inquiry	Conception, Research, and Design	1.5	1x0.5x*N*	Go – No Go Proposals
	Prototyping, Modelling, and Testing	4	2x0.5x*N*	**Midway presentations**
	Optimization, Iteration, and Analysis	2	1x0.5x*N*	Informal presentations of results
	Communicating	2	1x0.5x*N*	**Final presentations** and Lab Journal feedback
Second Open Inquiry	Conception, Research, and Design	1.5	1x0.5x*N*	Go – No Go Proposals
	Prototyping, Modelling, and Testing	4	2x0.5x*N*	**Midway presentations**
	Optimization, Iteration, and Analysis	2	1x0.5x*N*	Informal presentations of results
	Communicating	2	1x0.5x*N*	**Final presentations and Lab Journal grading**

2 Reflections and a continuing challenge

The two iterations of the Maker Lab show that it achieves most of its goals. The post-course student evaluation questionnaires and qualitative interview data clearly show reflection on and in-depth appreciation for the scientific process and strong motivation and self-efficacy for doing science. The student cohorts and the breadth of project topics also demonstrate the ability to serve multi-disciplinary cohorts.

The teaching methods are observed to have synergies and interdependencies. Open inquiry is enabled by accessible (Maker) equipment which students can learn to use on their own and on their own schedules. Flipped teaching methods give students more support with the difficult parts of the research process and are made possible when equipment is sufficiently safe and affordable for unsupervised use. This combination of open inquiry, flipped teaching, and use of Maker tools and thus constitutes a design feature which allows for retention of hands-on experimentation in remote teaching conditions [1].

3 Ensuing challenges

Common concerns about utilizing open inquiries include the difficulty in teaching specific experimental techniques and the worry that student-conceived inquiries will have a lower scientific quality. While both are valid observations, these concerns have been ignored in designing the Maker Lab because they do not relate to the above-stated course goals. Instead, the main challenge is the disparity between the instructor's worked time and compensated time, thus efficiencies in project guidance and student feedback are being pursued.

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