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Open Labs for Well-Educated Minds

Transforming the science lab into a more authentic investigation

Vincent Sicotte and Jean-François Désilets

The image we have of a science course is often rooted in the laboratory, perceived as a place for experimentation and discovery of the world. However, in CEGEP, as in high school, the reality of laboratory experiments often turns out to be a sequence of facts to be memorized and a string of equations disconnected from the real world. How can we transform these laboratories into fundamental elements of scientific understanding? Let's delve into this reflection by exploring the impact of open laboratories on the conception of science and its learning.

Context

The process of updating and redesigning the Science program, which began ten years ago, is now taking shape in local CEGEPs across the province. We saw this crucial step as an ideal opportunity to reflect on our practices and try to make the learning experience of young adults taking our courses more meaningful. A release granted by our academic dean confirmed that these were shared concerns.

At the heart of our approach: the physics *Mechanics* course, taught in the first year of the pre-university Science program, a course that's typically considered challenging, with failure rates approaching 30%. Even among those who pass the course, many struggle to make sense of their learning or transfer their knowledge to subsequent courses.

From the outset of our inquiry, it seemed to us that the laboratory should occupy a central place in our reflection: it's there that the equations of physics are tested and validated, and that they reveal all their predictive power. Laboratories offer more authentic learning situations and should occupy a central place in the pedagogical experience. According to the ministerial devis, practicums occupy in principle 40% of our contact hours, i.e. almost thirty periods in a session. Is this considerable amount of time being used to its full potential? Does the contribution of labs to learning and understanding correspond to expectations? Are there pedagogical methods specific to the laboratory that are more effective than others?

With these questions in mind, we first looked for answers in the literature, both to better define the problem and to find possible solutions.

What does one learn in a laboratory?

In educational circles, it's generally taken for granted that laboratory activities generate learning benefits. Nonetheless, decades of research on school science labs indicate that they are all too often missed opportunities (Hofstein & Lunetta, 2004). More recent evidence: Natasha Holmes, a physics professor at Cornell University, has been studying the pedagogical aspects of laboratories for 10 years. In a resounding study of nine physics courses at three universities (equivalent to our college courses), her team found that there is strictly *no added value* to learning through laboratory activities (Holmes *et al.*, 2017). Doing labs adds absolutely nothing, either in exams or in comprehension tests! The author and her team found a certain logic in these surprising results, since most of the laboratory activities identified are generally highly supervised and consist of obtaining a "correct" result through a series of imposed manipulations. In other words, in such laboratories, the challenge is simply to verify a law or a physical principle.

If prescriptive laboratory activities don't seem to promote learning, one of the arguments in their favour is that they at least teach the good old scientific method. But do they really? Clark Chinn, an educational psychologist at Rutgers University in New Jersey, has long been interested in these questions. In a typology of 468 laboratory activities offered to elementary and high school students in the USA, he concludes that most of them involve little or none of the cognitive processes of authentic science, and instead follow an algorithmic and prescriptive methodology. Doesn't repeatedly performing simplified, superficial and highly supervised tasks lead to an erroneous conception of science? The scientific approach is not simply a series of simple steps provided in advance, a "how-to" that always produces the same result. Rather, science is made up of questions, iterations and false leads; it is based on models that can be called into question. And the consequences can be serious, for young, developing brains: "When students learn an oversimplified, algorithmic form of scientific reasoning in school, they are likely to reject scientific reasons as irrelevant to any real-world decision making"[1] (Chinn & Malhotra, 2002, p. 214).

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[1] Social debates with a scientific component often give rise to misperceptions in public discourse: useful certainties are demanded of science. The COVID-19 pandemic was a case in point: the dialogue of the deaf between political discourse, rumours on social networks and scientific nuance resulted in a "massive global failure" (Sachs *et al.*, 2022).

Not only do "recipe"-type labs fail to contribute to the achievement of learning objectives, they could also foster a faulty epistemology in our scientists-in-training. So, which laboratory model(s) should we turn to? Unfortunately, the new Science program proposes nothing more than a continuation of the "verification" approach to laws and principles, unchanged for decades and yet criticized from all angles (Désautels, 2020; Cormier & Voisard, 2022). The compulsory program integrative assessment certainly offers a guided research experience, but arrives without adequate preparation. One thing is certain: in light of these observations, we can be dubious about the coherence between the means and certain goals of the program. Ultimately, graduates should be able to think and act critically and with intellectual rigour in a scientific context.

Open labs for better learning

In the 1960s, in response to the transmissionist paradigm of teaching (knowledge is passed on, intact, to good students), *discovery-based learning* developed, a movement placing investigation and exploration at the heart of the learning process. Inspired by constructivism, this philosophy was rooted in the work of pedagogical pioneers such as Piaget, Dewey and Vygotsky. This approach gradually found its way into schools, as awareness grew of the limited benefits of traditional laboratories (Hofstein & Lunetta, 2004).

"Open," "inquiry-based" or "guided research" laboratories allow greater latitude in the observation and characterization of real phenomena, in the formulation of measurement and analysis protocols, and even of research questions (Blanchard *et al.*, 2010). At the college level, such initiatives are emerging, to transform the traditional laboratory into an inquiry-based approach. For example, in chemistry, Cormier and Turcotte (2022) describe a laboratory where student teams have to extract ibuprofen from Advil capsules, with only a few general directions. Charles and colleagues (2022) show how the sequence of labs in a wave physics course culminates in the design of a wind or string musical instrument. In a biology course, teams work on a software platform to determine what ecosystem pressures have made the guppy fish spotted. A truly authentic research question!

Rather than following the chapters of a textbook or seeing the historical iterations of a theory in succession, we place student questioning at the center of learning. This open lab approach has well-documented benefits: it promotes understanding and retention (Abraham, 2011; Aditomo & Klieme, 2020) and positively influences attitudes toward science and its learning (Madsen, McKagan & Sayre, 2015)—more on this later.

Inspired by this movement, we turned our attention to *Modelling Instruction*.[2] In physics, a model (an equation) can be used to predict the parabolic trajectory of a falling object, for example, or the speed of an object after a collision. In chemistry, the modelling approach enables students to better understand the behaviour of gases or how energy is transferred from a system to its environment (Dukerich, 2015). In biology, the eukaryotic cell model can

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[2] It should be noted that the term *modelling* does not refer here to the pedagogical strategy of explicit teaching and applies mainly to the sciences.

be used to distinguish a bacterium (such as a bacillus) from a plant cell (Manthey & Brewe, 2013).

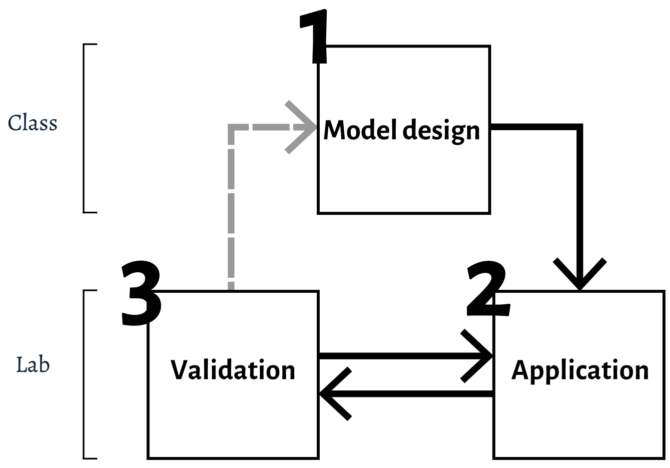
With its documented effectiveness, this strategy is undoubtedly the pedagogical reform that has had the greatest impact on pre-university science teaching in the USA (Jackson, Dukerich & Hestenes, 2008; Brewe, 2008). It is now widely implemented in American high schools and some universities. The reason for its success? This approach models the learning process on the scientific process itself.

Modelling at the heart of learning

Observation of real phenomena is the starting point for this process, rather than theory, concepts or equations, as is often the case. To follow up on these observations, student teams have to design *models* (graphical, schematic, algebraic), discuss them in large groups under teacher supervision, validate these models experimentally, then iteratively improve them based on measurements and results. We've tried to adapt this approach to the specificities of college reality. Here's the result.

Figure 1

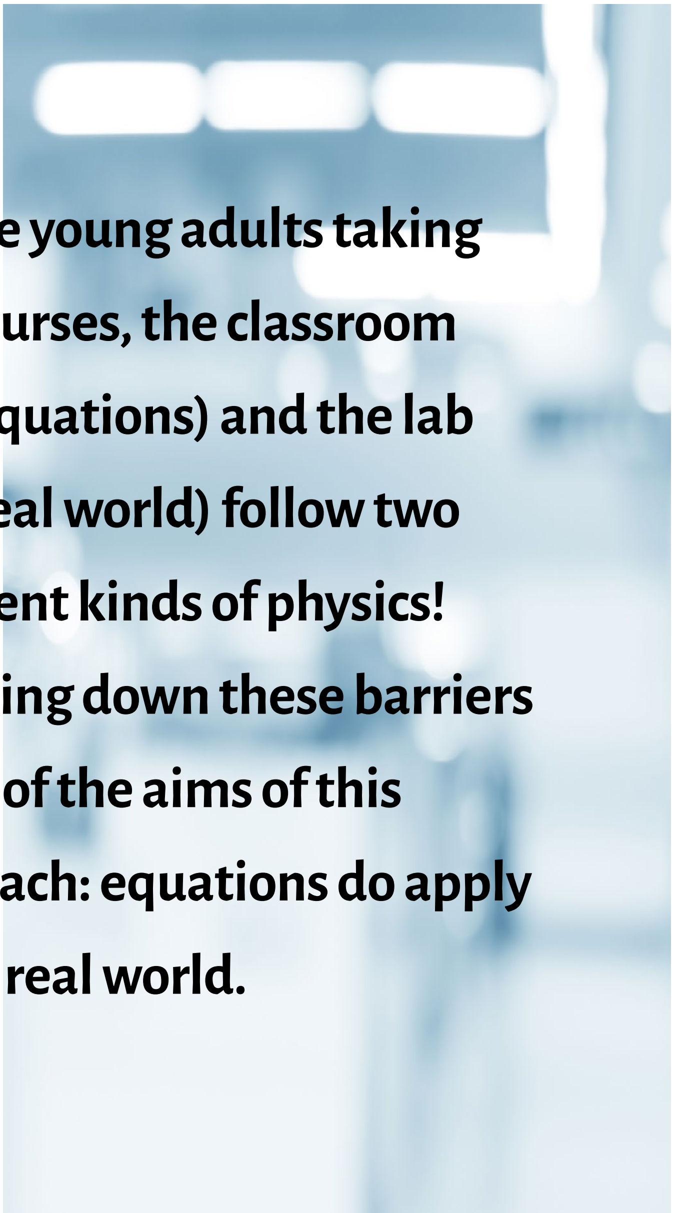
Modelling in the physics *Mechanics* course (based on Jackson, Dukerich and Hestenes, 2008)



The *design* phase takes place in the classroom. Based on a very brief description of the experimental situation to be studied in the laboratory, the student teams must use the notions of the course (concepts and general equations) to build a theoretical algebraic model, i.e. specific equations for this situation. The models developed must involve only parameters that can be measured in the laboratory. At this stage, a question often comes up: "Can we measure this in the lab?" Followed by the response, "What do you think?" For the young adults taking our courses, the classroom (the equations) and the lab (the real world) follow two different kinds of physics! Breaking down these barriers is one of the aims of this approach: equations do apply to the real world.

In the laboratory comes the model *application* phase, undoubtedly the one that contributes most to making the physics equations concrete: the teams have to determine how to measure the various parameters of their model, with the best possible precision. All the usual measuring instruments of a physics laboratory are available (balance, rulers, stopwatch, motion sensors with software interface). At this stage, the teachers must limit their interventions, at most guiding the teams in difficulty.

Finally, still in the laboratory, comes the *validation* phase. Based on measurements of the various parameters of their model, the teams can calculate the theoretical value of a result, then compare it with the experimental value of the same result (obtained differently). For example, does the calculated parabolic trajectory of an object match the measured drop point of a real marble launched in the laboratory? If the two results don't match, then the teams usually call on the teacher to point out their measurement errors. In vain, of course! Instead, they're invited to focus on the process: are the model parameters indeed those that were measured? Have they been measured correctly and accurately enough? A reflective process is set in motion, which brings the teams back to the application phase. Student teams are perfectly capable of achieving this level of autonomy and critical reflection, especially as they realize during the session that "it's all part of the game"! The idea that discipline-specific concepts and models don't always accurately represent reality is a fundamental lesson in learning: every theory has its limits



> **For the young adults taking our courses, the classroom (the equations) and the lab (the real world) follow two different kinds of physics! Breaking down these barriers is one of the aims of this approach: equations do apply to the real world.**

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In this dynamic, coaching is an important dimension. It's crucial that teachers and lab technicians learn to strike the right balance between "showing how it's done" and leaving teams completely to their own devices. Unfortunately, there are no instructions on how to find this balance, which must be defined collaboratively between staff members, but always with student learning in mind. While *guided* inquiry yields excellent educational results, *independent* inquiry, almost without supervision, shows rather negative results (Aditomo & Klieme, 2020). This means that if we leave student teams completely free, we run the risk of losing them...

In the modelling approach implemented in American schools, a return to the model *design* phase is possible if certain characteristics have not been taken into account (for example, non-negligible friction). This reinforces the idea that science is a dynamic process, a "work in progress" that leaves room for error. This back-and-forth is easier when the course takes place in a "studio" classroom, with laboratory equipment always available. In the reality of the college network, this return to the design phase (dotted line in the diagram) poses certain logistical challenges. Theoretical courses are rarely held in the same spaces as laboratories, so equipment is not readily available. For the first two iterations of our project, we couldn't find a way to allow this "back to the drawing board," which would bring a more authentic scientific approach to life. What's more, it was difficult to implement regular large-group discussions, an important component of this approach. These discussions have to take a very specific form (Desbien, 2002), with teams exchanging freely and comparing their theoretical models. This format is rather unusual for our Science students and would require repeated practice to be successful.

With this theoretical framework, we took a critical look at all our *Mechanics* labs, then transformed them into a guided research approach.[3] Using broadly the same equipment, we went from ten labs to five in a session, with some spanning more than a week. Supervision is reduced during the session to encourage autonomy. The experimental part of the course culminates in a three-week lab, where teams must formulate a research hypothesis. If we had to summarize our approach in simple terms, we could say: fewer instructions, more time!

A snapshot of attitudes in our classrooms

Our cohorts seemed to appreciate this approach, which was more open-ended than the laboratory activities of high school and other college-level science courses. As for the inquiry-based labs, where teams had to determine for themselves what to measure and how, three-quarters of respondents said they found this pedagogical strategy useful. Similarly, 74% agreed or strongly agreed with the statement "These labs helped me better understand physics concepts"; 72% agreed or strongly agreed with the statement "I wish the labs in other physics courses were like this."

And what about epistemology? Can we measure whether this inquiry-based laboratory approach influences ideas and conceptions about science? Among the standardized surveys that exist to measure changes in attitudes,[3] one of the most recent and well-known is the *Colorado Learning Attitudes about Science Survey* (CLASS) (Adams *et al.*, 2006). Designed for physics,[4] this survey does not aim to measure understanding or interest in this science, but rather to quantify the extent to which physics is perceived as a logical and coherent method for describing reality; how its learning is the result of a structured process (and not simply the consultation of a list of formulas).

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[3] Roughly twenty years ago, through a considerable amount of work, our department already adopted such an approach, moving away from prescriptive labs. But to maximize the number of experiments carried out, we put in place a number of supervisory measures over the years, reducing the freedom left to the teams. Ensuring the sustainability of a pedagogical transformation is a major departmental challenge.

[4] In the sense of beliefs or opinions, not learning attitudes.

[5] Versions also exist for other scientific disciplines (chemistry, biology, astronomy and mathematics).

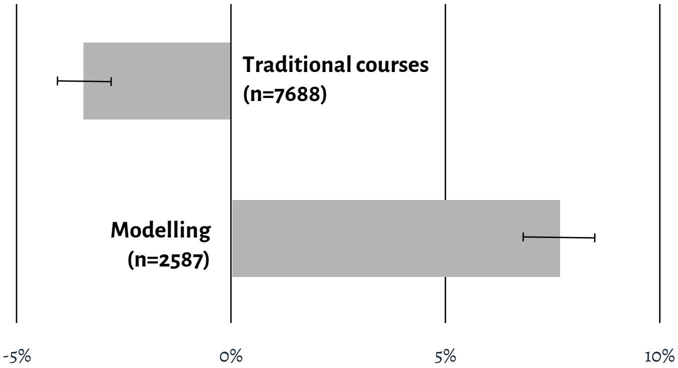
This survey consists of 42 questions to be answered on a scale of 1 to 5 (1 corresponding to "strongly disagree" and 5 to "strongly agree"), asked in the first and last classes of the session. Our translation is now considered the official French version of the survey.[6] Here's an overview of some of the questions: "A significant problem in learning physics is being able to memorize all the information I need to know"; "Knowledge in physics consists of many disconnected topics"; "There is usually only one correct approach to solving a physics problem." During the design of the CLASS, 16 professional physicists who took part in the process gave unanimous answers to 36 of the 42 questions (the nuances of the degrees of agreement [4 and 5] are merged, as are the degrees of disagreement). There is therefore a "correction key" to quantify the extent to which student attitudes toward physics are consistent with "expert" attitudes.

The evolution of ideas about science from the beginning to the end of the session provides valuable information about the effects of our pedagogical interventions. We'd like our class groups, after a whole session, to understand a little better how science works, and for student attitudes to approach expert attitudes. In other words, that the "post" results would be superior to the "pre" results. In fact, the opposite is true! As early as the first publications on CLASS, a troubling result was noted, then widely confirmed since: traditional pedagogies *deteriorate* attitudes toward science (Madsen, McKagan & Sayre, 2015; see Figure 2). At the end of a session, inaccurate perceptions about physics are even more widespread: it is regarded as facts to memorize, numbers to fit into meaningless equations, an activity with no relevance to their lives as young adults. After 15 weeks of listening to us, students understand even less about how physics works!

Surprisingly, this deterioration can be observed in both lecture-based courses and active learning classrooms. Active pedagogies generate better learning (Freeman, Eddy & McDonough, 2014; Von Korff *et al.*, 2016), but they do not improve attitudes toward science. Rather, the best attitudinal gains are associated with pedagogies modelled on the scientific process, where student groups work and discuss to experiment and collect data, build, test and then validate models. This is another argument in favour of the modelling approach.

Figure 2

Improvement and deterioration of student attitudes according to pedagogical strategies (based on Madsen, McKagan & Sayre, 2015)



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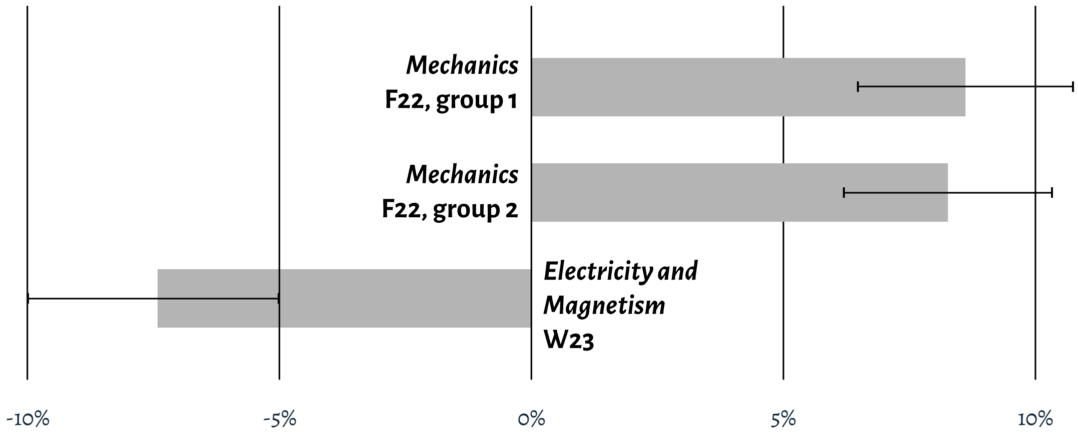
[6] The French version of CLASS is available for download from PhysPort, a platform that brings together various resources based on research into physics teaching [physport.org/assessments/assessment.cfm?A=CLASS].

In Fall 2022 (F22), during the first session of our survey-based laboratory implementation, we administered the CLASS to our groups and obtained significant gains of 8.2% (n=46) and 7.8% (n=39), respectively ($p < 0.01$) (see **Figure 3**). These statistics, representing the averages of individual variations between the beginning and end of the session, are comparable to those obtained through model-based approaches (see **Figure 2**, Modelling). They show that our groups not only have a slightly better understanding of how physics works, but also of how to learn it effectively. These encouraging results, obtained from the very first iteration of our action research, suggest that the changes made have been fruitful.

But did we have beginner's luck? To find out, we evaluated the fall cohort with CLASS in the Winter 2023 (W23) session, specifically in the subsequent physics course (*Electricity and Magnetism*). This course had not undergone any changes based on a modelling approach, either in the laboratories or in the theoretical classroom. **Figure 3** summarizes the results: gains for our two groups with the modelling approach in F22, then, a shift of student attitudes away from expert beliefs in W23, with CLASS scores decreasing by an average of 8.0% (n=49). In terms of attitudes, the cohort unfortunately seems to have returned to its starting point. At the very least, this confirms that the changes made to the *Mechanics* course have had positive effects on attitudes, in addition to providing a more authentic learning experience.

Figure 3

CLASS survey variations in Fall 2022 and Winter 2023



Conclusion

After questioning ourselves on the best ways to enable our science groups to give meaning to their learning, we undertook a transformation of the physics *Mechanics* course laboratories based on the pedagogical literature. Here are the main findings and lessons from this transformation.

Open labs offer a better learning experience but require concerted change. They represent a paradigm shift from more prescriptive approaches, but this evolution seems necessary to take full advantage of the investment (in time and resources) that labs represent. Teachers need to adjust their practices, giving *less instruction but more time*. Interventions need to be less directive, focusing on process rather than outcome: *answering questions with questions* is a good way to go! Without doubt, this new paradigm takes learners out of their comfort zone, but three quarters of them enjoyed the experience and saw it as a positive contribution to their learning objectives.

This mode of inquiry brings about positive changes in attitudes toward science and learning. Isn't one of our aims as educators to provide a better understanding of how science really works? Of course, the young adults in our courses won't all go on to careers in physics, but they will all take part in tomorrow's social debates. A well-educated society debates better.

In any pedagogical transformation, flexibility and openness are the keys to success. We've tried to adapt a very specific pedagogical strategy (learning by modelling) to the college reality, which in many ways is quite different from that of American high schools. It's not a failure to realize that certain aspects are not transferable. To ensure the sustainability of a change, rather than applying a ready-made recipe in its entirety, it's better to keep the most promising transferable aspects of a pedagogical strategy, encourage contributions and applications by other colleagues, and allow ourselves to make mistakes!

If you're interested in adventure, "the beginning is half of everything," said Pythagoras. Start with your existing physics set-ups or chemistry protocols, make your biology labs more open, transform one or two of them into a guided inquiry: you'll turn them into learning experiences that will benefit your students in every way. It's a "recipe" ... to experiment with! ▬

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