Designing Inquiry Based Labs for College-Level Biology Students

Karl Laroche, Vanier College, Montreal, Canada, larochek@vaniercollege.qc.ca
Elizabeth Charles, Dawson College, Montreal, Canada, echarles@dawsoncollege.qc.ca
Michael Dugdale, John Abbott College, Montreal, Canada, michael.dugdale@johnabbott.qc.ca
Sean Hughes, John Abbott College, Montreal, Canada, sean.hughes@johnabbott.qc.ca
Kevin Lenton, Vanier College, Montreal, Canada, lentonk@vaniercollege.qc.ca
Rhys Adams, Vanier College, Montreal, Canada, adamsr@vaniercollege.qc.ca
Caroline Cormier, Cégep André-Laurendeau, Montreal, Canada, caroline.cormier@claurendeau.qc.ca
Véronique Turcotte, Cégep André-Laurendeau, Montreal, Canada, veronique.turcotte@claurendeau.qc.ca
Chao Zhang, McGill University, Montreal, Canada, chao.zhang2@mail.mcgill.ca

Abstract: We report on a practitioner-researcher crafted semester-long biology inquiry-based lab approach which implemented a new script based on conceptual progression. Students were required to make decisions in well-scaffolded contexts relating to each component of the scientific process separately, but progressing in an order supporting the knowledge and skills to be learned, from experimental design and statistical/procedural methods, to formulating hypotheses, and ultimately drawing conclusions. In each module, students took up agency for a single component, but scaffolded within an exploration of the entire scientific process, including reflecting on how their work integrated into a full pre-prepared journal article. The progression concluded with students completing a small comprehensive project on their own. Results were encouraging, as students met the significant challenge of the final project, meaning our approach could serve as a model for other biology instructors. Further research will explore the success of the various scaffolds employed.

Objective

Inquiry-Based Labs (IBL) is an instructional approach based on social constructivism and aimed to promote the learning of scientific practices and processes. It focuses on engaging students in the thinking and procedures by providing them with opportunities to make decisions as part of the laboratory component of a science course. It is a departure from traditional verification/confirmation labs that often look like recipes from cookbooks, leaving little room for students to use skills and knowledge that are central to scientific experimentation and analytical skills (Holmes & Bonn, 2013). Increasingly, higher education science programs are questioning the effectiveness of using traditional labs (Holmes et al., 2020). The effectiveness of IBL arguably relies on appropriately scaffolding decision making and supporting the knowledge construction used in task completion (Hmelo-Silver et al., 2007).

To date, most theoretical and empirical research with IBL has been based on types of single labs (e.g., Blanchard et al. 2010), and there is little evidence-based information to guide the design and development of a college-level biology IBL curriculum. This paper reports on a semester-long IBL that explores a new script for IBL based on a "*conceptual progression*", instead of that proposed as typical implementations, as described in other studies.

Background and design

The literature has used two dimensions to classify the IBL approach: (1) the amount of instructor guidance (decision-making autonomy/agency afforded to students), and (2) the stage in the scientific process selected for the decision-making activity (research question, methods, results analysis, discussion). Science education researchers (Blanchard et al., 2010; Buck et al., 2008) have classified IBL implementations into typologies based on the intersection of these factors, which associate higher levels of inquiry with increased student decision-making (agency), but which constrain and prescribe the stages where this decision-making takes place. According to these typologies, lab activities with lower levels of inquiry (i.e., higher levels of instructor guidance) all encourage student agency only in the late stages of the scientific process (drawing conclusions), while providing strict guidance throughout all early stages. Inquiry levels are then constrained to progressively and sequentially increase backwards through the earlier stages (analyze data, design methods, formulate hypothesis, ask RQ). Essentially, per these typologies, students are only afforded agency to make decisions for first steps of the scientific process when they can complete an activity requiring them to make decisions throughout the entire process. While this *backward progression* seems typical of IBL described in the literature, it arguably does not reflect an ideal conceptual progression for IBL and overlooks the interdependent nature of each stage of the scientific method. Furthermore, those studies categorize individual labs in isolation and do not explore sequencing across a course, a critically important aspect to practitioners.

The semester-long IBL intervention on which we report sequenced lab modules by the specific knowledge and skills to be learned, following what we believed to be an ideal conceptual progression and unconstrained by the backward progression identified in other studies. Each module required students to make decisions associated with its particular learning objectives, while prompting them to integrate the associated knowledge into the larger process of scientific experimentation. In this way, students were progressively required to consider each component of the scientific process separately in a well-scaffolded context, and finally to put their understanding of each component together in a more comprehensive small project. The IBL was the product of a practitioner-researcher partnership, with both collaborating equally and extensively to adapt existing lab activities within the framework of our ideal conceptual progression model.

Context of the IBL case study

The IBL case study was set in a college-level General Biology I course (first year university equivalent, first biology course in the Science program), the institution situated in the province of Quebec, Canada. It consisted of five lab modules, each focusing on a particular aspect of the scientific process, which is the key characteristic of our approach. We also designed a variety of scaffolds to support the task completion. Typically, these scaffolds were embedded in the module as part of the instruction, or as background information, rubrics and models of high-quality performances.

Importantly, one of the scaffolds used in this IBL case study is embedded in the affordances of an online platform called OCLaRE (Online Collaborative Laboratory Reporting Environment). This is based on a "writing-to-learn" pedagogy (Reynolds et al., 2012) with structural features and templates that format the components of a typical lab report into the layout of an authentic scientific journal article. In our IBL modules, we used these affordances in a "complete-the journal article" activity, which required students to reflect on their choices for the particular aspect of the scientific process when viewing their section of the article within the context provided by the entire paper.

Lastly, the design team collected all student output, including lab reports within the online platform, which together we consider the biology-focused performance data. To assess the implications of this design on learning we developed a suite of instruments: a pre-post-test to assess changes in scientific reasoning (George's Ice Cream, adapted from McDermott, 1995), an epistemic belief questionnaire (Topic Specific Epistemic Beliefs, Strømsø, et al., 2008), and a survey and interview questions on perceptions rela(ted to the course and levels of confidence.

Design of the IBL case study

The first IBL module was significantly more elaborate than the other four because it developed skills needed throughout the rest of the semester. It focused on providing opportunities for decision-making related to analytical skills, specifically aimed at developing the ability to design simple experiments and use simple statistical methods. The curriculum develops these skills first because we consider them the bedrock upon which other components of the scientific method are built. For example, the appropriate statistical/analytical tools to use depend on the study design and data collected, and proper interpretation of results for the purposes of drawing conclusions is challenging without understanding these two elements together. Simultaneously, a proper scientific hypothesis needs to be testable, so students must be able to conceive of how a hypothesis could be tested before they can formulate one. Thus, in module 1 students made choices to design an experiment to test a hypothesis about sugar content in peaches, to run a statistical analysis using data provided, and ultimately to produce a results section for a scientific article,

IBL module 2 was on measurement protocols and data manipulation, module 3 on using background information to formulate hypotheses, and module 4 on drawing conclusions and inferences from results (see Table 1). These modules were adapted from current lab practices and were thus presented in an order which reflected the content and regular lab activity progression of the course: in module 2 students designed a study to determine whether particular plant and animal cells were different in size, in module 3 students used detailed background information to formulate a hypothesis about the pattern of inheritance for a particular fruit fly gene, and in module 4 students used results of an experiment to draw conclusions about which evolutionary mechanisms had led to changes in allele frequencies for a gene in controlled fruit fly populations. However, the order of the interventions also reflected what we view as a logically coherent progression for scaffolding development of scientific skills, by first establishing the fundamental understanding of design and analytical methods, building upon this to formulate testable hypotheses, and finally considering the entire process and drawing conclusions. Collectively, these four modules represent the main components of the scientific method, but also map to the four sections of a traditional scientific publication.

The final component of this five-part curriculum, IBL module 5, was an open-ended task which required students to write a full scientific paper. This was based on a SimBio simulator called "How the Guppy Got Its Spots", which itself is modeled directly on a classic paper in evolutionary research (Endler, 1980). The simulator roughly reproduces the environment where the research took place, including the tools Endler used to run the experiments. Given Endler's research question, students had to formulate a hypothesis, design an experiment using the simulator to test this, analyze the raw data output, and draw conclusions. Scaffolding the IBL, students were provided with a full grading rubric, support documentation that accompanies the simulator, and the actual Endler (1980) publication that the simulator is modeled on. A social annotation assignment, using an online platform, was generated for the latter.

Elaborating on the conceptual progression model (see Table 1), it's important to note that the decreased number of decisions associated with modules 2-4 belie the complexity of the reasoning and knowledge resources required to complete these modules. For module 2, students needed to consider and describe procedural constraints associated with taking measurements of cell sizes, as well as assumptions about cell shape that would be required to manipulate data for the purposes of comparison. These constraints/assumptions were not explicitly provided but were critical to assess confidence in the results and conclusions. For modules 3 and 4, the background knowledge required to formulate a hypothesis or interpret results and draw inferences was quite complex for students at this level. Scientific inquiry is rooted in a deep understanding of the subject matter, and the final tasks associated with these two lab modules required students to draw heavily upon fundamental conceptual knowledge from the course.

Table 1
The five-module (Mod.) curriculum outlining the conceptual progression model of students' decision making

	Student choice	Mod.1	Mod. 2	Mod. 3	Mod. 4	Mod. 5
Introduction	Form hypothesis from background information			x		x
	Write introduction			x		x
Methods / Design	Design experiment from RQ and hypothesis	x	x			x
	Incorporate replication into design	x	x			x
	Systematically vary independent variable	x	x			x
	Write methods		x			x
Analysis, Discussion, and Conclusions	Select appropriate analytical approach	x				x
	Interpret data and draw inferences				x	x
	Write results	x				x
	Write discussion and conclusion				x	x

Implementation script

The workflow of the first four IBL modules followed a five phase "script" (Dillenbourg & Jermann, 2007). Phase 1 was a synchronous lab activity focused on teaching the identified skills and/or collecting data. In most instances this meant that students were introduced to the research question and worked together to answer that question, while, notably, the identified decision-making task was foregrounded. Working through the components of the scientific method together in groups acted as a scaffold for the particular element students needed to explore themselves. For phase 2, students were asked to write a draft of the paper section being targeted by that module. To assist with the completion of this task, they were provided with scaffolds that included standards and criteria as well as models of quality performance. Materials included: reviews that they completed in the synchronous lab, videos of particular methods where appropriate (necessary for online labs), descriptions of the goals of that written section and how they related to the scientific method, a detailed grading rubric which would be used to assess their work, and a highquality student submission from similar student work in previous semesters which was annotated to identify strengths and weaknesses. In phase 3, students submitted their draft section using OCLaRE. As described earlier, the objective of this phase was to have students consider a coherent scientific report of the entire process that links the storyline of the pre-written sections to the student-written section. OCLaRE inserted their draft section of the paper into a full high-quality student report submitted in a previous semester, and allowed students to view the entire paper in proper publication format. For phase 4, students were asked to complete a reflection assignment. They considered their own submission, as well as examples of the pertinent paper section of varying quality, all relative to the full publication describing the entire scientific process obtained from OCLaRE and the particular criteria required to properly complete the specific section. Lastly, phase 5, students completed the final draft of the section of the paper and submitted.

Discussion and relevance

The conceptual progression approach to IBL instruction was conducted within the context of a larger three-year study on the mechanisms and value of inquiry-based learning, and data from the semesters are still being processed and analyzed to attempt to answer larger research questions. To date, generally speaking, the results of this case study are encouraging for our practitioner-researcher team. Notably, student artifacts achieved standards consistent with high level quality at the introductory college level.

Given the nature of this practitioner-researcher project, it is important to note that the different stakeholders view the results differently. The course instructor (first author) is most interested in the results of the final module, which required students to undertake and make decisions throughout the entire scientific process, each of which would impact downstream decisions and have consequences on the final product. Thus, while the total of our IBL intervention could be perceived as simply providing an algorithm to follow of the scientific method, students could not have produced the high-quality papers submitted for the open-ended final module simply by following a recipe. Rather, the outcome could potentially be better perceived as having provided the students with an iterative set of decision-making practices, focused initially on each step of the process separately, but which students were ultimately able to compile together successfully, possibly due to our emphasis throughout of viewing each step within the context of the whole. Meanwhile, the researchers are curious and skeptical, currently examining the results of each module and which scaffolds were taken up and which were not. In particular, one focus for further investigation is the role played by OCLaRE. Those data are yet to be examined closely to identify how the task of reading through a full scientific article in the "complete-a-journal" activity mediated the understanding of the experimental process, as a whole.

In summary, from the data collected and analyzed to date, it appears that providing students with the agency to make decisions for all steps of the scientific process, with the exception of formulating a research question, is challenging and requires the design of additional scaffolds. That said, results of a post-semester survey indicate that, while the final assignment was extremely challenging, student confidence in having been prepared to meet that challenge was high. In the view of our instructor (first author), the students did indeed display their ability to meet the challenge, assessed by the quality of their final lab reports. In addition, most students displayed acceptable to impressive levels of competency for every stage of the scientific process and outcome, evaluated by a grading rubric designed for a typical biology course. Thus, from a practitioner's perspective, this approach to IBL can be deemed a success, and could serve as a model for other biology instructors with first year undergraduate students. From a researcher perspective, this case study, of what we are calling a "conceptual progression" IBL model, provides insights into the process of designing and scaffolding for students' autonomy and the release of agency.

References

Blanchard, M. R., Southerland, S. A., Osborne, J. W., Sampson, V. D., Annetta, L. A., & Granger, E. M. (2010). Is inquiry possible in light of accountability?: A quantitative comparison of the relative effectiveness of guided inquiry and verification laboratory instruction. *Science education*, *94*(4), 577-616.

Buck, L. B., Bretz, S. L., & Towns, M. H. (2008). Characterizing the level of inquiry in the undergraduate laboratory. *Journal of college science teaching*, *38*(1), 52-58.

Dillenbourg, P., & Jermann, P. (2007). Designing integrative scripts. In *Scripting computer-supported collaborative learning* (pp. 275-301). Springer, Boston, MA.

Endler, J. A. (1980). Natural selection on color patterns in Poecilia reticulata. *Evolution*, *34*(1), 76-91.

Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: a response to Kirschner, Sweller, and Clark. *Educational psychologist*, *42*(2), 99-107.

Holmes, N., & Bonn, D. (2013). Doing science or doing a lab? Engaging students with scientific reasoning during physics lab experiments. 2013 Physics Education Research Conference Proceedings.

Holmes, N. G., Keep, B., & Wieman, C. E. (2020). Developing scientific decision making by structuring and supporting student agency. *Physical Review Physics Education Research*, *16*(1), 010109.

McDermott, L. C. (1995). *Physics by Inquiry: An Introduction to Physics and the Physical Sciences, Volume 2*. John Wiley & Sons.

Reynolds, J. A., Thaiss, C., Katkin, W., & Thompson, R. J., Jr. (2012). Writing-to-learn in undergraduate science education: a community-based, conceptually driven approach. *CBE Life Sci Educ, 11*(1), 17-25.

Strømsø, H. I., Bråten, I., & Samuelstuen, M. S. (2008). Dimensions of topic-specific epistemological beliefs as predictors of multiple text understanding. *Learning and Instruction*, *18*(6), 513-527.