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It Takes Time: Learning Process of Science through an Integrative, Multi-Semester Lab Curriculum

Janet M. Batzli, Michelle A. Harris, and Seth A. McGee
University of Wisconsin-Madison, Biology Core Curriculum, 250 N. Mills St, Madison, WI 53076, USA
(**jcbatzli@wisc.edu; maharris@wisc.edu; samcgee@wisc.edu**)

What does an integrated multi-semester, process of science-based lab curriculum look like? And what do students really learn? This paper outlines teaching goals, learning outcomes, affordances and challenges of a multi-semester biology core lab curriculum. We describe how we organize and scaffold skill development over time, and how we create an agile curriculum that changes with emerging knowledge of the discipline and is scaled to 115 students/semester. We share key details of our process of science teaching approach, how we integrate science communication and statistics, and sample assessments aimed to foster the development of scientific reasoning over time. Finally, we feature undergraduate students voices who describe their experience diving into questions and experimentation on their first day of class and how they progress as scientists over 2-3 semesters. We then discuss process of science components that are critical for sustaining this type of multi-semester, developmental curriculum.

Keywords: process of science, experimentation, curriculum scaffold

Introduction

Process of science skills, such as scientific reasoning, science communication, developing hypotheses and performing experiments, engaging in scientific discourse, and giving and receiving feedback on scientific ideas are essential elements to practicing authentic science yet these skills take a great deal of time to develop-- more time than is typically allotted in a one semester undergraduate lab curriculum. Upper-level or capstone labs often aim to help students achieve these skills but encounter challenges with students' differential preparation. Process of science skills form the central unifying theme that defines the learning progression of a three-semester, integrated lab course sequence within the Biology Core Curriculum (Biocore) at University of Wisconsin-Madison www.biocore.wisc.edu (Batzli 2005).

Biocore lab courses are an example of course-based undergraduate research experiences or CUREs that have gained recent attention as an approach to engage students in research early in their college experience (Corwin et al. 2014). The Biocore program philosophy and pedagogy, its emphasis on the iterative and integrative nature of science and the importance of teaching and learning science as it is practiced, was built in 1967—three decades before the national call to do so in The Boyer Report (1998). Biocore's student learning outcomes focus on process of science skills and scientific reasoning that together form the basis of scientific inquiry and are aligned with outcomes described in AAAS's Vision & Change in Undergraduate Education (2011). Furthermore, these process of science outcomes together with essential social skills (e.g. problem-solving in teams, giving and receiving feedback, interpersonal communication) are aligned with those identified as important by employers (Hora et al. 2016).

Three-semester Lab Curriculum

Scientific research, collaborative group learning, integrative thinking, and communication (written and oral) are the four main emphases of the Biocore lab curriculum and provide the framework for the learning goals (Table 1).

Students typically begin Biocore their sophomore year after foundation coursework in math and chemistry. Biocore lab course topics are in general alignment with concurrent Biocore lecture courses. Most Biocore students require two of the three lab courses for their major requirements, but many students choose to take all three lab courses, using the third lab course to fulfill upper level lab requirements.

All lab courses are scheduled for a 3h lab time preceded by a 50 min required discussion section. Total course enrollment ranges from ~45 (Biocore lab III) to ~115 (Biocore lab I & II) split into 3-5 sections of 16-24 students each.

Biocore lab I (Ecology, Genetics and Evolution lab) starts in the Biocore Prairie (a 12-acre prairie restoration on the UW Madison campus) on the first day of class. Students take a 'five senses tour' to begin their in-depth observations of plants, animals, evidence of microorganisms, and interactions with the abiotic environment. In the following four weeks, each student is assigned to a team of 3-4 peers to develop a testable question, propose and carry out an experiment, interpret data and generate conclusions based on evidence. The ecology unit is followed by a four-week unit on genetics using anthocyanin pigment production in Wisconsin Fast Plants as a model system (Batzli et al. 2014). The semester concludes with an evolution unit where student teams propose a novel experiment on evolution in Darwin's finches and an expedition to the Galapagos based on historic and contemporary finch data.

Biocore II (Cellular Biology) starts with a one-week exploration of basic cell and molecular biology equipment and techniques (i.e. micropipetters, analytical balance, pH meter, microscopes- light, phase contrast and fluorescent, spectrophotometers, centrifuges, vortex, incubators, water baths) and then launches into the first four-week unit focusing on enzyme catalysis and the importance of molecular structure and function using alkaline phosphatase as a model system (Harris et al. 2009). Next, student groups dive deeply into a five-week unit on the molecular genetics of heat shock factors and proteins in *C. elegans* using RNAi and GFP modified proteins to detect changes in gene expression (Cox-Paulson et al. 2012). The last five weeks of the semester is spent on signal transduction using the yeast mating system as a model (see Harris et al. in this ABLE 2018 Tested Studies for Laboratory Teaching Proceedings for reference).

In Biocore lab III (capstone lab), students are assigned into permanent teams of 3 to 4 for the entire semester and given substantial autonomy to develop a completely novel question based on animal physiology for the first 8 weeks and plant physiology for the final 7 weeks. Teams are challenged to build sophisticated biorationale to support a research question that they create based on readings in the primary literature and their own pilot data. Teams have a large array of model systems to choose from (invertebrate and vertebrate) including *C. elegans, Daphnia*, mice, tadpoles and some decide to work with humans. All student research using mice and tadpoles must adhere to an approved vertebrate animal use (campus RARC) protocol. Student projects using humans as model systems must use non-invasive, safe protocols that are approved by the instructor. There is more emphasis on feedback, pilot studies and revision, and each project goes to much greater depth than either of the two previous semesters.

Each multi-week unit for three semesters (one and one-half years of classroom-based research experience) uses the same general curriculum scaffold: observation, question generation, propose experiment, give and receive feedback, do experiment (revise and repeat experiment) and communicate conclusions. The detailed curriculum scaffold along with timeline, process of science learning goals, example laboratory activities and assessments are outlined in Table 1.

Upon transition to each new unit, students reflect on their learning as a class, and are asked to evaluate themselves and each member of their team according to their strengths and weakness as a collaborative group. In Biocore I and II labs, students are then assigned new research teams and proceed to the next unit. While nearly all process of science skills are attempted in each unit, new skills are emphasized and honed in an iterative and developmentally appropriate way- first semester focuses (with substantial guidance) on testable questions, biorationale, hypothesis development, variation and raw data analysis, and introductory written science communication. The second semester (with less guidance and more autonomy) focuses on experimental design, statistical analysis, data interpretation, conclusion development, and intermediate written communication. In the third semester (with least guidance and most autonomy) teams develop their own protocols, troubleshoot and seek council from experts (on campus and off), further advance their statistical analysis skills and gain even more confidence in written and especially oral science communication.

Supporting Scientific Communication and Statistical Analysis

When students begin Biocore Lab I, they are given our Biocore Writing Manual and Biocore Statistics Primer (materials are available online www.biocore.wisc.edu/bioresources). The Writing Manual summarizes our communication expectations and has rubrics for papers, oral presentations, and research posters. Students use this same Biocore Writing Manual across all 3 semesters, thus our expectations are rigorous but also consistent. Students write proposal and final research papers in all three semesters, and present one formal team presentation in Biocore Labs I and II. The capstone lab III particularly emphasizes oral scientific communication by requiring teams to present one ungraded and two graded formal presentations. Expectations for statistical analysis increase each semester and are supported by the Biocore Statistics Primer customized to our process of science lab curriculum.

Timing and Iteration Matter

How long does it take for students to achieve process of science goals? Biology is not linear, and neither is the process of science. Both the concepts and competencies that define biological science benefit from an integrated approach to teaching and learning, which takes time. Although we have not done a comprehensive systematic evaluation on how students develop as scientists over the multi-semester lab sequence, we have a number of shorter term and cross-sectional analyses that directly assess student learning of process of science skills (Myers and Burgess 2003; Phillips et al. 2008; Cox-Paulson et al. 2012; Batzli et al. 2014). In short, we have found that there are several key features to student learning that can be realized over a multi-semester (at least two semesters), integrated lab sequence that are much less possible or impossible in one semester.

1. Sophisticated understanding of the logic and reasoning of a biological rationale- the reasoning that describes why the hypothesis is logical and why research is being done.
2. Efficient and effective literature search approach for self-learning of background information necessary to develop relevant testable questions.
3. Critical thinking, trust and respect of peers in the learning community to deliver and receive constructive, productive feedback in written and oral form.
4. Scientific language and thorough understanding of the scientific method to apply an efficient approach to experimentation, scientific writing and communication.

In the first semester course (Biocore I), we begin this process by having students experience several cycles of asking questions, proposing research, gathering data, and making conclusions—in a fairly guided manner. As the curriculum moves to the second semester (Biocore II) and third (Biocore III) students gain familiarity for how research progresses, each research unit becomes less guided, more rigorous and students develop their identity as researchers and scientific writers and speakers. With each step and each iteration, there are opportunities for students to gain experience outlining a research question, presenting a research proposal for feedback, writing a research proposal in the form of a paper or scientific poster, giving and receiving feedback through peer review, getting feedback from instructors, gathering data and, finally, communicating research results in the form of a formal presentation, scientific poster or paper. Since students progress together in their cohort they gain a common learning experience (the highs and lows), a collaborative approach, a familiar 'process of science' language, and buy-in to a shared set of learning goals. With each subsequent experience, instructors help students achieve these ambitious goals by continuing to calibrate and adjust the curriculum in order to balance the degree of challenge students face and support they receive. "*Set the bar high, keep it consistent, and help students get there*" has become our instructional mantra.

At the end of the semester, we asked students how confident they were in their capacity to engage in the process of science. Approximately half responded they were very or extremely confident after Biocore I and II, and the vast majority (>88%) were very to extremely confident after semester III. In one students' words at the end of Biocore II:

"I would by no means claim that I've mastered these (process of science) skills, but I've definitely made substantial progress. It's not that these goals are unreasonable, but that they describe skills that I believe we can continue to work on during future research experiences. That being said, I feel that I've developed a foundational understanding of scientific research through Biocore labs that most student don't obtain through typical undergraduate courses. Because the program allows students to work with the same professors over multiple semesters, we get to pick up right where we left off after breaks and keep working to meet the consistent high expectations as a unified team."

Key Affordances & Challenges

Process of Science Components

- *Student ownership in novel questions:* Students are highly motivated to develop their own questions rather than being given a question or a set to choose from. *Challenge:* Logistics of supporting numerous independent research projects at the same time.
- *Informal feedback presentations:* Student teams present their research proposal and solicit feedback from their peers. They open their ideas to criticism, and are asked to exchange constructive feedback. *Challenge:* Keeping pace with students' projects and thinking deeply, critically, constructively enough to provide high quality feedback.
- *Biological rationale:* Most students are unfamiliar with the "why" of a hypothesis when they begin college science coursework. Through iterative cycles of inquiry and revision, students gain appreciation for the importance of the 'BR' and why it is a fundamental part of the scientific reasoning that makes the hypothesis compelling and worthwhile to test. *Challenge:* A thorough BR takes a great deal of background knowledge (from molecules to biosphere) and experience that is difficult to attain in earlier units.
- *Support Materials:* Instructors in each course write customized lab manual chapters that support each unit. Often lab manual chapters are co-written by graduate or postdoctoral teaching fellows who are closer to the science (and the bench) than lead instructors. Given the heavy emphasis on writing and statistical analysis, we have developed the Biocore Writing Manual and Statistics Primer to provide guidance and define expectations with a complete set of rubrics (materials are available online www.biocore.wisc.edu/bioresources). *Challenges*: Maintaining and attaining high expectations and standards of scientific rigor in rubrics while recognizing and fostering student progress.

Learning Community Components

- *Student peer community*: The student community forms initially through iterative rounds of group work. Students can enter our physical lab spaces at any time with key code access, and are held to high standards with an ‘Honor Code’. By the end of the second semester, almost every student in the cohort has worked with one another. Cross cohort relationships form through peer mentoring and more senior students serving as undergraduate TAs in the lab courses. As students progress, they build their individual identity as a scientist and gain a learning community with a set of standards and norms for how science is done. *Challenge:* fostering a growth mindset in the face of failures inevitable in science and facilitating team dynamics.

- *Instructor comfort and openness:* Instructor openness, authentic curiosity and investment in student ideas. When an instructor respects the students process and meets them where they are, students are more likely to buy-into the difficult process of ‘real science’, to engage in science discourse, receive critique and constructive feedback. *Challenge:* Learning to be comfortable with not knowing and learning from students.
- *Cohesive teaching team:* Our core instructor team for 3 semesters of lab consists of two full-time instructors and one lab manager. The instructors generate curriculum, teach labs, mentor graduate and undergraduate teaching assistants, and direct all aspects of the course. The lab manager is not ‘behind the scenes’ but rather out front, visible and accessible, helping students on the ground as they reason through their questions, construct unique protocols, and trouble shoot experiments. *Challenge:* Providing consistent, high quality feedback and continuity of communication within large teams of instructors, and with multiple lab sections.

On balance, the affordances outweigh the challenges, with many students achieving a high level of intellectual maturity as scientists through their multi-semester lab experience in Biocore. It is with this evidence in mind that convinces us of the value of this multi-semester approach to teaching process of science.

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About the Authors

The authors work as a teaching team providing continuity to a three-semester lab curriculum. Janet Batzli serves as the Associate Director of Biocore and as an instructor in Biocore lab I (ecology, genetics, evolution) and Biocore lab II (cellular biology) since 2002. Michelle Harris is an instructor in Biocore lab II (cell biology) and Biocore lab III (organismal biology) where she has taught since 1999. Seth McGee is Biocore's lab manager where he provides umbrella support and guides student inquiry into novel questions in all three lab courses.

Table 1. Typical research unit curriculum scaffold iterated two to three times over the course of the semester

Week	Process of Science Learning Goals *Students should be able to:*	Example Lab Activities	Example Assessments (formative & summative; group or individual; graded or non-graded)	Student Learning Experience (Quotes from two students)
1	• Make careful observations • Ask testable, relevant, creative scientific questions	• Introduction to unit, topic, concepts • Tour through area (Biocore Prairie), tour through legacy data, jigsaw tour of equipment toolkits • Practice observations, practice assays (Myers and Burgess 2003; Cox-Paulson et al. 2012)	• Pre-lab concept check; clicker questions; concept map diagrams • Tentative testable question • Experimental design worksheet	"Our goal of the first lab was to make careful observations and come up with questions. I was very excited about the open-endedness, and my team came up with many questions that we found interesting."—Ownership is key "On the experimental design worksheet we were asked to organize our knowledge about our study system into a biological rationale figure that eventually leads to our hypothesis. Our team struggled with this part especially."
2	• Gather & interpret relevant information in context from scientific literature • Generate logical bio-rationale • Make predictions and formulate hypotheses • Anticipate expected and alterative results and implications • Give and receive feedback (verbally)	• Informal Feedback presentations (group) • Mini-workshop on experimental design • Mini-workshop on science communication (writing, finding and reading literature)	• Questions & answers and follow-up discussion during feedback presentations	"Throughout the two semesters of lab, I now feel confident interpreting scientific texts and using literature to develop a biological rationale." "With feedback from the teaching team and our peers, in discussions and informal feedback presentations, we were able to improve our skills. As I was trying to give useful feedback to my peers in lab, I also learned to think more critically about the process we use in lab to answer our own study question."
3	• Develop protocols to test hypotheses • Give and receive written feedback	• Pilot studies and data collection • Group-Instructor consult	• Individual research proposal paper/ poster (see Biocore Writing Manual with guidelines and rubrics www.biocore.wisc.edu/bioresources) • Peer review of each other's research proposals	"Although challenging, with the help of the Biocore Writing Manual, suggestions from professors or TAs, and feedback from my peers, I learned new techniques to communicate more effectively and with greater clarity. For example, by using figures and tables, I could replace lengthy paragraphs with easier to understand visuals."
4	• Analyze data and make logical conclusions utilizing statistical reasoning • Evaluate assumptions associated with experimental design and biological system • Give and receive written feedback	• Complete data collection • Data visualization • Data analysis • Group-instructor consult	• Pre-lab on data analysis approaches and statistics (Remsburg et al 2014) • Instructor feedback on proposal (writing conference discussion with instructor)	"Writing a proposal or a final paper presents a different challenge than organizing experimental design into a (oral) presentation. With each paper I write, along with the feedback I got from the teaching team, I became more confident and proficient in formulating the ideas behind a study–arguing for my hypothesis using sources and logical arguments, as well as presenting our experimental design."
5	• Give effective oral presentations • Give and receive written feedback • Write and communicate about scientific research	Final project presentation (group)	• Formal graded presentation/individual or group paper or poster (Batzli et al. 2014) • Response to reviewers essay (custom question based on final presentation to evaluate capacity to generate valid conclusions based on the data generated)	

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