The College Science Learning Cycle: An Instructional Model for Reformed Teaching

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ABSTRACT
Finding the time for developing or locating new class materials is one of the biggest barriers for instructors reforming their teaching approaches. Even instructors who have taken part in training workshops may feel overwhelmed by the task of transforming passive lecture content to engaging learning activities. Learning cycles have been instrumental in helping K–12 science teachers design effective instruction for decades. This paper introduces the College Science Learning Cycle adapted from the popular Biological Sciences Curriculum Study 5E to help science, technology, engineering, and mathematics faculty develop course materials to support active, student-centered teaching approaches in their classrooms. The learning cycle is embedded in backward design, a learning outcomes–oriented instructional design approach, and is accompanied by resources and examples to help faculty transform their teaching in a time-efficient manner.

INTRODUCTION
A variety of factors inhibit broad implementation of evidence-based teaching practices by postsecondary science faculty (Hativa, 1995; Handelsman *et al*., 2004; Henderson *et al*., 2010, 2011; Brownell and Tanner, 2012). Some instructors are merely unaware or unconvinced of the need for change, while others who wish to change lack the training (Miller *et al*., 2000; Winter *et al*., 2001; Tagg, 2012). Even after receiving training, faculty can struggle to fully implement newfound approaches due to lack of time, incentives, or feedback/support from peers (Yelon *et al*., 2004; Pfund *et al*., 2009; Dancy and Henderson, 2010; Ebert-May *et al*., 2011; Henderson *et al*., 2011; Brownell and Tanner, 2012; Borrego and Henderson, 2014). These barriers result from attempts to reform educational practices within organizational structures that do not yet support or reward such activities. The thousands of current and future educators who have received excellent training through efforts like the National Academies Summer Institutes (Pfund *et al*., 2009) or the Faculty Institutes for Reformed Science Teaching (FIRST IV; Ebert-May *et al*., 2011), among others, may struggle to work within their current time constraints to make the changes necessary to better serve their students. Regardless of approach, transforming a traditional lecture into a student-centered active-learning classroom takes time: time outside class to develop new instructional materials to support and evaluate the new approach and time in class to develop the expertise to effectively implement new strategies (Krockover *et al*., 2002; Stanulis *et al*., 2016). To address this challenge, this paper introduces an instructional model—a learning cycle—to provide college science faculty with a consistent, structured approach to constructing teaching materials for a reformed scientific classroom. This learning cycle is based on the Biological Sciences Curriculum Study (BSCS) 5E model and can be used with any evidence-based, active-learning approach. As presented in this paper, it can stand alone or be embedded in backward design (Wiggins and McTighe, 1998).

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HISTORY OF SCIENCE LEARNING CYCLES

For decades, elementary, middle school, and high school teachers have used learning cycles to design instruction and improve student learning (Karplus and Thier, 1967; Thier *et al.*, 1970; BSCS, 1995; Bybee *et al.*, 2006). The stages of learning cycles provide a structure and order to cognitively engage students in activities that mimic scientific approaches to problem solving. One of the earliest learning cycles for science classes was the Science Curriculum Improvement Study (SCIS) model, a three-stage cycle consisting of exploration, invention, and discovery (Karplus and Thier, 1967). This cycle starts with student-driven information acquisition, followed by an introduction of terms and concepts by the instructor, and finishes with student application of the newly acquired knowledge to a novel situation. On the basis of the success of the SCIS model, Bybee *et al.* (1989) developed the BSCS 5E learning cycle, one of the most widely used models today. The middle three stages—explore, explain and elaborate—are modified versions of the SCIS cycle, bookended by two new stages—engagement and evaluation (Table 1). The 5E is firmly grounded in constructivism, with the initial phase eliciting students' prior knowledge on the topic. The new final phase aids in metacognitive development by offering both the student and instructor opportunities to gauge students' progress toward the learning objectives addressed by the instructional unit. Like the SCIS model, multiple studies have found improvements in learning gains for students in classes employing the BSCS model (Bybee *et al.*, 2006).

THE COLLEGE SCIENCE LEARNING CYCLE

Like the BSCS, the College Science Learning Cycle (CSLC) introduced here builds on the structure and success of previous models. The CSLC maintains the first and fifth stages of the BSCS and condenses the middle three into one, returning to a three-stage cycle: engage, construct, and evaluate. The goals of the first and last stages overlap with the corresponding stages in the 5E model. The first stage uses a relevant topic or hook to interest students in the topic and engage them in activities to draw upon previous knowledge. It can also include elements of exploration, which are often closely linked with engagement. The final stage serves to evaluate student knowledge before moving on to a new topic, with particular focus on big picture synthesis. Instead of forcing college instructors into activities that emphasize exploration, explanation, and elaboration, in that order, the new middle stage of the CSLC promotes knowledge construction by involving students in activities that promote practice of scientific skills and working with concepts in order to maximize successful achievement of the desired course learning outcomes. This stage includes elements of the three middle stages of the BSCS, giving the instructor the flexibility to determine the types and order of activities that best aid student learning. The goal of this adaptation is to make the learning cycle more accessible and appealing to college science instructors while retaining the benefit of its structure for guidance and consistency.

Backward Design

The CSLC can be used independently or in the context of backward design, an approach to course development that emphasizes learning over teaching (Wiggins and McTighe, 1998). Backward design consists of four steps: 1) stating specific learning outcomes for students; 2) determining the evidence that will demonstrate whether students achieve the outcomes; 3) creating learning activities to help students achieve the outcomes; and 4) finally, comparing the products of the first three steps to ensure that they match (Figure 1). It is during the third step of backward design, development of learning activities, that the CSLC comes into play.

The approach is termed "backward" because it reverses the more traditional approach, which tends to skip specific learning outcomes and focuses on organizing and delivering content with development of assessments occurring after instruction. Instructors using backward design start by identifying learning outcomes that guide the development of the assessments and learning activities and keep the focus on the learner rather than the teacher. The most useful learning outcomes state very specifically what students should know or be able to do by the end of the course. Their efficacy lies in using assessable verbs like "predict," "calculate," or "diagram." Most syllabi, however, contain learning goals stated with broad, not obviously testable verbs like "understand," "know," "learn," or "appreciate." To move from broad goals to testable outcomes, instructors can envision what action(s) a student might take to prove that he or she understands a specific concept. For example, most biologists expect that life sciences majors will understand natural selection by the end of their degree programs, but what does it mean to *understand* natural selection? How could a student demonstrate this understanding? The ability to explain, using the mechanism

TABLE 1. Comparison of the CSLC with the SCIS and BSCS models

SCIS model	BSCS 5E model	CSLC model	Description of the stages of the CSLC model
	Engagement (new)	Engage (similar to 5E)	Engage interest and prior knowledge with a question, task, dilemma or problem
Exploration Invention (Term Introduction) Discovery (Concept Application)	Exploration (adapted SCIS) Explanation (adapted SCIS) Elaboration (adapted SCIS)	Construct (new)	Construct new knowledge by involvement in deliberate practice to achieve desired learning outcomes, e.g. acquire content knowledge, conceptual understanding, critical-thinking and or scientific process skills, attitudes and behaviors regarding science
	Evaluation (new)	Evaluate (similar to 5E)	Evaluate ability to apply new knowledge, understanding, skills and relate to the bigger picture (synthesis)

Adapted from Bybee *et al.* (2006).

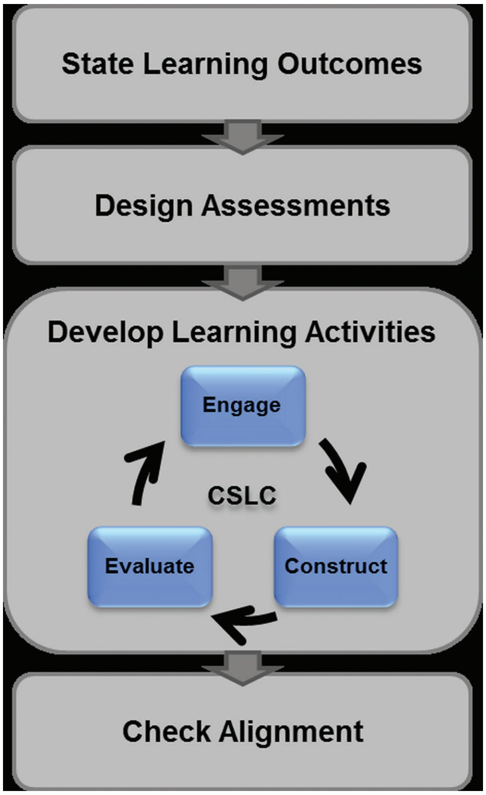

FIGURE 1. The CSLC embedded in backward design. The gray boxes and arrows represent the stages of backward design. The blue boxes and black arrows represent the stages of the CSLC embedded in the "develop learning activities" stage of backward design.

of natural selection, how traits in subsequent generations of organisms change in response to a given change in their environment is an assessable outcome of students gaining an understanding of natural selection. Progressing from broad goals to assessable outcomes can be challenging at first, but like any new strategy, it becomes easier with practice. Additionally, instructors can avoid redundant work by consulting available resources to make the process quicker and easier. Department committees typically tackle curricular mapping, which involves identifying learning outcomes for the major. If this level of support is unavailable, educational committees of disciplinary societies may provide this information through the society's website. Finally, professional and educational organizations publish reports or materials that may include learning outcomes, for example, Vision and Change (American Association for the Advancement of Science [AAAS], 2011), Next Generation Science Standards (NGSS; www.nextgenscience.org), and CourseSource (www.coursesource.org).

With specific learning outcomes in hand, instructors can more effectively design assessments that determine how successful students are in accomplishing the outcomes. The previous learning outcome lends itself to an obvious assessment question: "Using your understanding of natural selection, explain how the average running speed of subsequent generations of gazelles increased following the introduction of cheetahs to their habitat." Answers to this question allow instructors to gauge their students' understanding of the mechanism of natural selection. Well-stated learning outcomes inform development of assessment questions, because they use action verbs that students can carry out in order to reveal their level of understanding of a concept or proficiency with a skill. Like the scientific method, backward design is an iterative process. The act of constructing assessment questions can make the desired learning more apparent, allowing the instructor to revise learning outcomes accordingly.

When developing course learning activities, it is important to keep the desired learning outcomes in mind. Engaging students in activities for the sake of being active is considered a "sin of design," because it does not support student achievement of the learning outcomes (Wiggins and McTighe, 1998). The concept of deliberate practice tells us that, in order to master a concept or skill, one must spend sufficient time engaged in activities that directly relate to the desired understanding or expertise (Ericsson *et al.*, 1993). Having a clear picture of what constitutes successful achievement of a learning outcome offers a target at which to direct learning activities for deliberate practice. For example, a course that trains students to run a marathon in 4.5 hours will be taught very differently than a course that trains students to sprint a 100 meter dash in 13 seconds. Likewise, students in science courses who are expected to master graph interpretation will have to spend a significant amount of time interpreting graphs; watching their instructors interpret graphs in front of them for 4 years will not suffice. In keeping with the previous example of natural selection, activities that constitute deliberate practice for this concept would offer scenarios in which population traits changed in response to an environmental perturbation and would prompt students to work in groups to explain the phenomena using the mechanism of natural selection. For some concepts, a single activity may suffice to help students achieve the desired understanding, but more often, students need to take part in a coordinated series of activities to achieve the ultimate learning outcome.

It is at this point that the CSLC provides a logical framework to help instructors design a cohesive instructional unit that specifically addresses desired learning outcomes. With the focus on the learner, rather than the teacher, the first stage of the CSLC guides instructors to determine what their students already know about the subject and whether they harbor any misconceptions. During the second stage of the CSLC, instructors create activities that help students build on what they know to construct a coherent understanding of the concept that is evaluated in the final stage before moving on to a new topic.

When all learning outcomes, assessments, and learning activities are in place, the final step in backward design entails comparing the products of the first three steps in order to identify mismatches. An example of a mismatch is when students must analyze natural scenarios and explain how natural selection leads to the outcomes on an examination but passively listen to their instructor explain the concept during class. In this example, the students are not required, during instruction, to perform the same tasks that are required on the exam. Unfortunately, this is a not uncommon type of misalignment between instruction and evaluation found in traditional lecture classes.

By focusing on the teacher, the traditional approach does not compel the instructor to contemplate whether the teaching methods being used truly foster mastery of the content or whether mastery of content is the only desired outcome. While acquiring disciplinary content is necessary, it is not the only learning that instructors expect of their students. When polled, instructors from all institutional types cited critical thinking/problem solving, data interpretation, and communication as the top three most important skills for undergraduates in science to acquire (Coil *et al*., 2010). These skills all require cognitive processing beyond simple recognition or memory. Problem solving is broadly described as the application of reasoning and logic to arrive at a solution to a puzzle (Anderson, 1990; Burns and Vollmeyer, 2000) while critical thinking applies reasoning and logic to the task of analyzing a situation in order to arrive at a judgment (Halpern, 1989). However, while the respondents were unified in their conviction that mastering these and other scientific process skills was critical, the majority admitted they did not spend sufficient time teaching these skills. The power of backward design is that once specific learning outcomes are made explicit, gaps in the desired outcomes and mismatches between the outcomes and the methods for teaching and/or testing them become apparent.

CSLC Stage 1: Engage

Stage 1 of the CSLC encompasses two important steps when introducing a new topic or concept: 1) pique students' interest and 2) gauge students' prior knowledge.

Piquing Student Interest. An important component of the "engage" stage of the CSLC is to provide a context that piques the students' interest by relating the content being taught to a relevant topic (Garcia *et al*., 2015). Some instructors use themes such as stem cells to organize the topics for an entire course, while others use different "hooks" for each concept or topic, like cystic fibrosis for membrane transport, cancer for cell cycle, and phenylketonuria for gene expression (Garcia *et al*., 2015). Most instructors have likely used this method for at least some of the topics that they teach or have obvious examples from their own scientific experience—their research, the research journals they read, or "hot" science topics in the news—that they could implement. For those looking for guidance to make this a more systematic approach, Science Education for New Civic Engagements and Responsibilities has been leading the charge to improve science education by training faculty to incorporate topics of societal relevance that interest students. This organization hosts a comprehensive website (SENCER.net) with useful examples and resources to aid faculty in finding and implementing topics of interest in their courses.

Gauging Prior Knowledge. The educational theory of constructivism informs us that students do not arrive at our classrooms as empty slates upon which we write new knowledge (Dewey, 1966; Ausubel, 2000). In actuality, students arrive with a variety of experiences that shape their preconceptions. Some of these preconceptions are accurate and some are not. Left unchallenged, misconceptions are exceedingly hard to displace (Science Media Group, 1989, 1996). Introducing a new topic with activities that require students to use prior knowledge to answer a question or solve a problem allows students to reinforce the correct and confront the incorrect preconceptions (National Research Council [NRC], 1999b). Additionally, if the learning activity requires students to share their responses with the class, the instructor receives immediate feedback about the general state of understanding, thereby avoiding boring students by teaching concepts that they already know or confusing them by skipping material that they do not.

A variety of techniques can effectively assess students' understanding at the beginning of an instructional unit. Preclass quizzes or activities, especially online versions that allow easy grading, provide a quick snapshot of student understanding before class. Just in time teaching is a good example of how student performance on preclass activities is used to direct class instruction (Novak, 1999). Another simple and easy-to-use activity for evaluating prior knowledge is brainstorming. Students respond immediately, or after brief discussion with a peer or group, to an open-ended question. Effective brainstorming prompts are big picture questions that get students thinking about the topic but do not require much specific prior knowledge.

For example, at the beginning of a unit on cellular division, the instructor could prompt a brainstorming session with either of the following:

> "If binary fission and mitosis each function as asexual reproduction, why do we have both?"
>
> "List all of the known functions for cellular reproduction."

Instructors can address more specific questions with group problem solving or immediate response systems (clickers) that allow them to poll the audience on multiple-choice or fill-in-the-blank questions (Guthrie and Carlin, 2004; Hall *et al*., 2005). A simple group problem-solving technique for introducing a topic is to pose a complex question, one that students should be able to answer by the end of the unit, and require students to identify what they already know or would need to know to be able to answer the question. The following is an example of this technique that I use to introduce membrane transport in my introductory biology course: "What do you know or need to know in order to answer the following question: Which of the following can pass directly through the cell membrane: oxygen (O_2), carbon dioxide (CO_2), water (H_2O) or potassium (K^+) ions?" In my large-enrollment introductory biology course for majors, this question always elicits answers related to the size of the molecules and ions and their water solubility. I then use the student answers to organize further instruction during the "construct" phase of the learning cycle. In addition to providing valuable information about prior knowledge, this technique also gives students practice approaching a problem space where they must identify knowns and unknowns and come up with an approximation of how to get from one to the other (Polya, 1945). My freshmen are so unaccustomed to this practice that the first few times they are asked to do it in my course, they often do not even know what they are being asked to do.

Clicker questions are particularly useful for posing questions about known misconceptions (Caldwell, 2007; Sevian and Robinson, 2011; Maskiewicz *et al*., 2012; Lyubartseva, 2013). For example, when beginning a unit on photosynthesis or the nutrient cycles, instructors can probe a common misconception about carbon cycling by posing the following question: "From what source does an acorn get the majority of its biomass as it grows into an oak tree? A) air, B) soil, C) water, D) sunlight." Answers from my introductory biology students are fairly evenly split across all four answers with "air" being the least commonly chosen answer. Students then must discuss and defend their answers in their groups before I repoll the question (Mazur, 1997; Smith *et al*., 2009, 2011; Knight *et al*., 2015). Following the second polling, students offer explanations to the whole class for why the right answer is right and the wrong answers are wrong.

CSLC Stage 2: Construct

After introducing students to the topic and evaluating their prior knowledge, the second stage of the CSLC focuses on deliberate practice of the skills and concepts stipulated by the intended learning outcomes. College science students are faced with a variety of learning challenges. They must acquire a vocabulary of science terms, an understanding of the basic concepts in the discipline, critical-thinking and problem-solving skills, science process skills, and an appreciation of the nature and process of science. With the diverse array of information options available at our students' fingertips, disseminating information is no longer a necessary role for instructors. Out-of-class activities that require students to work with simpler, fact-based material free class time for learning activities that focus on the more difficult concepts and critical-thinking skills. This allows students to develop deeper conceptual understanding of complex processes and practice critical-thinking and science process skills in the presence of the instructor, who can provide real-time feedback and guidance. For courses that require students to remember a large amount of fact-based material, online quizzing platforms that provide repeated recall not only help prepare them for class but improve long-term storage of the content (Karpicke and Roediger, 2007).

Many resources exist (e.g., Angelo and Cross, 1993; Handelsman *et al*., 2007; Hoskins, 2010; AAAS, 2011; Tanner, 2013; Dirks *et al*., 2014; http://teachcreate.org; www.coursesource.org) that provide examples and instruction for the use of a variety of learning activities, from think–pair–share (Allen and Tanner, 2002) to case studies (Boehrer and Linsky, 1990). The sheer number of different learning activities available can be bewildering to a new practitioner. A primary goal of the CSLC is to make the process of developing learning activities less overwhelming. When transforming an existing course from passive to active learning, it is not necessary to discard all old materials and start from scratch. The decision tree in Figure 2 walks instructors through a few simple questions to determine whether and how their existing material can be modified for use in the active-learning class.

When evaluating existing materials, the first step is to determine the purpose for including the material. Does inclusion of this information help fulfill a learning outcome? If not, get rid of it. Discarding unnecessary material is easier in theory than practice. Almost all instructors struggle with the content "monster," wherein feelings of apprehension or guilt accompany not covering every detail of a topic. If class time was unlimited, including all of the content would cost nothing. In reality, class time is fleeting and out-of-class time is divided among many other courses and activities. Including content for its own sake takes students' time and attention away from the most important concepts and skills, leading to superficial and short-lived knowledge. An actual example of this comes from an introductory biology course taught by a novice instructor. A neurobiologist by training, the instructor included detailed coverage of each clade of protists during the biodiversity unit. This treatment left no class time for addressing fundamentally important concepts such as the evolutionary transitions from prokaryotes to eukaryotes or from single-celled to multicellular organisms. Furthermore, during the second iteration of the course, the instructor realized that she had forgotten much of the detailed information on the different groups of protists, begging the question, what did the students learn during this unit?

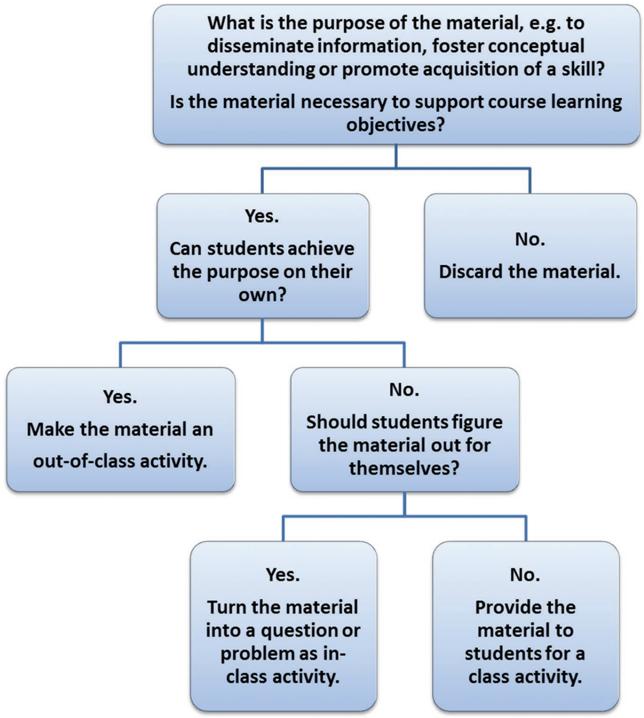

FIGURE 2. Decision tree for transforming existing materials for passive lectures into learning activities for active, student-centered classes. For any course material, start at the top and answer the questions to determine the recommended action for the material.

If material supports course learning objectives, the next step is to determine whether it requires class time. Shift basic information that students simply need to recognize or know out of class, leaving class time for more difficult concepts and skills. For example, when studying cellular reproduction, simply knowing the order and function of the stages of mitosis is information that students could acquire on their own through a preclass quiz or assignment. However, grappling with the outcome of perturbations that interfere with various aspects of the process requires analyses that would benefit from group discussions and interactions with the instructor. Learning activities that prompt students to predict and explain the outcomes of mutations that alter the steps of mitosis would allow students to use basic content to develop a more sophisticated understanding of an important and complex cellular process.

In-class material falls into two very broad categories. The first is material the instructor disseminates to students in order that they may use it to better understand a complex concept or process. For example, an instructor could illustrate how the complex biochemical processes of cellular respiration are used to generate cellular energy and then expect students to work in groups to determine how enzymatic inhibitors or mutations would change the functioning of the system. Students gain a working understanding of the system by analyzing the impact of the perturbations. In addition, repeated practice with this type of logical approach to understanding scientific processes helps students build critical-thinking skills. The second category includes concepts with which students need to struggle to achieve their own "aha" moment. For example, simply telling students that carbon dioxide from the air provides the majority of biomass as an acorn grows into a mature tree is not sufficient to disabuse them of the common misconception that the majority of the biomass actually originates from soil, sun, or water. Posing this as a clicker question, with common misconceptions as distractors, sets up a dissonance moment when the student realizes that his or her previous knowledge is incorrect and works with the new information to construct a more accurate understanding.

As instructors make the transition from passive to active learning, an empirical approach allows for fine-tuning of techniques and activities to maximize student learning. Turn tasks that are too easy into preclass preparation assignments. If a task is too hard, the activity shifts from a desirable level of difficulty that can aid learning (Bjork and Bjork, 2011) to learning paralysis. Feedback from students is useful in identifying how to modify the material to shift it back to a cognitively challenging but doable task. When instructors find themselves performing tasks that students should do for themselves, for example, solving problems or explaining solutions, it is time to modify course materials.

CSLC Stage 3: Evaluate

While the assessments created during the second stage of backward design are intended to evaluate learning at the completion of an instructional unit, assessment activities incorporated during the instructional unit provide timely information to both student and instructor about the student's progress. Synthesis activities in the evaluation stage of the CSLC are intended to reveal whether they have attained the desired level of competence before moving on to the next topic. These assessment activities can be very specific or can take the form of bigger picture tasks that require synthesis of several concepts. For instance, at the end of an instructional unit on natural selection, ask students to determine whether given scenarios are examples of natural selection or to create an example of natural selection from some starting criteria (see Box 1). This example of an evaluation-stage activity demonstrates how easy it can be to turn previously passive teaching materials, that is, the instructor simply telling the students how they would have to modify the 100 meter dash to make it natural selection, into an effective and fun formative assessment by turning the material into a question or problem to be solved by the students. When the students are also required to explain or defend their answers, these activities provide valuable feedback on their progress toward the learning goals, which helps both the teacher and the students correct misunderstandings and gauge whether more time is required for successful acquisition of the concept or skill.

THE CSLC IN ACTION

The preceding section characterized each stage of the CSLC using a variety of examples. Here, I will use a single topic from introductory biology to illustrate how the CSLC fits into the third step of backward design (Table 2). This example, developed at the 2004 National Academies Summer Institute (Madison, WI), targets the process of gene expression, expressly how information in the DNA of a gene codes for the particular order of amino acids that make up its protein. Table 2 describes learning activities for each stage of the CSLC. Briefly,

- *Engage*: A genetic disease, phenylketonuria (PKU), hooks students' interest in how mutations in genes result in dysfunctional proteins that cause the symptoms of the diseases. Students then contemplate a big picture question about how genes code for proteins and determine what they need to know to answer the question; this engages both prior knowledge and logical processing of the situation.
- *Construct*: A series of clicker questions deconstructs the larger process and allows students to grapple with each step. Next a group activity requires students to use their newly acquired understanding to identify the reading frame for a gene using the amino acid sequence of its protein and the mRNA codon table. This is a difficult challenge for introductory students and takes a significant portion of class while

BOX 1. Darwin at the Olympics: Example of a CSLC Evaluation Activity

Darwin at the Olympics

<u>Group work prompt:</u> "Using your understanding of natural selection, modify the 100-meter dash in such a way that it becomes natural selection."

<u>Report out:</u> Following the group work period, answers are collected from groups (this can be all groups in a small class or a subset from large-enrollment classes).

Once the list of answers has been displayed, the class evaluates each answer with a thumbs-up for examples of natural selection, thumbs-down for answers that are not natural selection, and a flat hand, palm to the floor, for "I don't know." Following the class vote, groups either volunteer or are called upon to explain why they do or do not deem each example to be natural selection. The following are some common types of solutions offered by student groups (students are instructed to dismiss ethical or moral considerations, as this is a hypothetical scenario):

1. "Add hurdles."
2. "Make the runners run over rocky, uneven ground."
3. "Release a tiger behind the runners."
4. "Kill the losers."
5. "Only the first two runners across the finish line can reproduce."

<u>The feedback on student learning:</u> This assessment activity immediately identifies which groups have achieved the desired understanding of natural selection and which have not. Some answers, like the first two, reveal that students have simply changed the competition but do not yet realize that they must connect the outcome of the competition with either survival or reproductive fitness in order to create an example of natural selection. The third and fourth answers connect the outcome of the race to survival, while the final answer connects the outcome of the competition directly to reproductive fitness. The groups' explanations of their answers also give insight into why students arrive at the wrong answer. Groups that give answers like number 2 work very diligently to make the race more complicated or difficult because "natural selection is important and should select for more than one thing."

TABLE 2. CSLC in action: gene expression

Identifying desired learning outcomes

Broad learning goal: students will understand how the information in a gene codes for the amino acid sequence in a protein.

Specific learning outcome: students will be able to predict changes in the amino acid caused by specific mutations.

Design tools to assess achievement of learning outcomes

Given a specific portion of a gene, the amino acid sequence for which it codes, and the mRNA codon table, students will be able to predict the change that will occur in the amino acid sequence in response to a mutation.

Develop learning activities to promote achievement of learning outcomes

Engage

Interest hook: phenylketonuria (PKU)

1. Show students a picture of the warning to phenylketonurics on the side of a diet soda can with the heading "Poison pop" and ask: "Why is this warning label here?"
2. Show a short video clip of a young woman with PKU recounting a childhood memory associated with having PKU.
3. Provide some specific information about the genetic nature of the disease and the symptoms

Engage prior knowledge: group problem solving—"What do you know?" and "What do you need to know?"

Group activity: list three things that you know or need to know to answer the following question:

Genetic diseases, like PKU, confirmed that there is a link between DNA and proteins.

Below is a segment of a gene and part of the amino acid sequence that would result from translating the DNA sequence.

Which nucleotides are responsible for this particular sequence of amino acids?

3′CGTTTTACCAAACCGAGTACTGAG5′
5′GCAAAATGGTTTGGCTCATGACTC3′
TRP-PHE-GLY-SER

Construct

During the opening group problem-solving session, students typically identify the three things that they need to know to answer this question:

1. There are many more nucleotides than amino acids, so it is not likely to be a one-to-one coding between the two.
2. There are two strands of nucleotides but only one chain of amino acids, so it is likely that only one strand of DNA codes for the nucleotides.
3. The DNA strands have directionality, so you have to know which way to read it to get the right coding for the amino acids.

The following series of clicker questions engage students with these three issues.

1. If there are 20 different amino acids in proteins and 4 different nucleotides in DNA, which of the following is *sufficient* for nucleotides to code for all the amino acids?
   a. One nucleotide codes for one amino acid
   b. Two nucleotides code for one amino acid
   c. Three nucleotides code for one amino acid
   d. Four nucleotides code for one amino acid
   e. More than four nucleotides code for one amino acid
2. What is the DNA sequence in the *template strand* for a protein with the amino acid TRP (tryptophan)? (Hint—template means pattern, so the template strand is the strand that the RNA polymerase READS to build the mRNA). The next three questions need the mRNA codon table.
   a. 3′UGG5′
   b. 5′UGG3′
   c. 3′ACC5′
   d. 5′ACC3′
   e. 3′TGG5′
   f. 5′TGG3′
3. What is the DNA sequence in the *coding strand* for a protein with the amino acid TRP (tryptophan)? (Hint—the coding strand is the complementary strand to the template strand)
   a. 3′UGG5′
   b. 5′UGG3′
   c. 3′ACC5′
   d. 5′ACC3′
   e. 3′TGG5′
   f. 5′TGG3′

(*Continued*)

TABLE 2. Continued

4. Group work: Which nucleotides are responsible for this particular sequence of amino acids (this sequence of amino acids comes from the middle of a protein)?

   3′CGTGGTACCAAACCGAGTGGTGAG5′
   5′GCACCATGGTTTGGCTCACCACTC3′
   TRP-PHE-GLY-SER
   Which strand is the template strand?
   What is the reading frame (where is the beginning and end)?

5. If the DNA sequence below were shortened by removing the underlined nucleotide, what would be the expected result when compared with the original?

   3′CGGTCGT<u>A</u>CAGGTGACGCCAGC5′
   a. The amino acid sequence would be unchanged.
   b. The sequence will be shortened by one amino acid.
   c. The amino acid sequence would be shortened by several amino acids.
   d. There would be a different sequence of amino acids after the deletion.
   e. No product would be produced.

Evaluate

The following is a homework activity that integrates the different aspects of gene expression that students practiced during the construction stage in class. This activity offers students additional practice as well as providing the necessary evaluation of the students' ability to apply their understanding in a larger context. Based on their performance on this activity, the instructor can choose to revisit problematic issues or move on if students have achieved the desired level of mastery.

Homework: PKU mutation activity

Background on PKU

PKU is caused by the lack of functional phenylalanine hydroxylase enzyme. This enzyme is responsible for converting the amino acid phenylalanine (PHE) into tyrosine (TYR). Phenylalanine hydroxylase is 452 amino acids long, and several different mutations have been discovered. Different mutations affect the activity of the enzyme to different extents. Cases of PKU vary in severity, with more severe cases showing higher levels of phenylalanine. High levels of phenylalanine are toxic to developing nerve cells and can cause brain damage in children.

Assignment

Below are several different phenylalanine hydroxylase alleles from human populations. For each allele, the first line is the amino acid sequence of the protein starting at a given position. The second and third lines are the DNA sequences in a portion of the gene for this protein. The normal alleles are followed by examples of mutations.

Choose one of the PKU gene sequences and:

1. Identify the coding strand and reading frame
2. Highlight the mutation
3. Write out the new amino acid sequence that would result from the mutation
4. Predict based on the result whether the effect would be normal, mild or severe.

Normal #1

#256 Gly Gly Leu Ala Phe Arg Val Phe
5-GGGATTTCTTGGGTGGCCTGGCCTTCCGAGTCTT-3
3-CCCTAAAGAACCCACCGGACCGGAAGGCTCAGAA-5

Mutant #1a, found in Swiss sisters and their offspring.
5-GGGATTTCTTGGGTGGCCTGGCCTTCCAAGTCTT-3
3-CCCTAAAGAACCCACCGGACCGGAAGGTTCAGAA-5

Mutant #1b, identified in German and Turkish patients.
5-GGGATTTCTTGGGTGGCCTGGCCTTCTGAGTCTT-3
3-CCCTAAAGAACCCACCGGACCGGAAGACTCAGAA-5

Normal #2

#51 Leu Phe Glu Glu Asn Asp Val Asn
5-CGCTTATTTGAGGAGAATGATGTAAACCTGACCCACATTGAATCTAGA-3
3-GCGAATAAACTCCTCTTACTACATTTGGACTGGGTGTAACTTAGATCT-5

Mutant #2a, multiple ethnic associations
5-CGCTTATTGAGGAGAATGATGTAAACCTGACCCACATTGAATCTAGA-3
3-GCGAATAACTCCTCTTACTACATTTGGACTGGGTGTAACTTAGATCT-5

Check for alignment of cognitive levels

The desired outcome—being able to predict changes in the amino acid sequence of proteins caused by mutations in genes—is echoed in the assessment question, which forces students to make just such a prediction. The learning activities, both in and out of class, deconstruct the process of gene expression into stages that help students build understanding of various embedded concepts (e.g., codon, reading frame, template and coding strand, directionality of DNA) necessary to successfully predict the impact of mutations on the structure of proteins.

they struggle to understand the information transfer from gene to protein.

- *Evaluation*: A homework assignment that uses known human mutations in the PKU gene requires students to extend and assess their ability to decipher how coded information in DNA determines protein structure and to accurately predict the impact of mutations on protein structure and function.

ADVICE FROM THE TRENCHES

What can one expect when implementing an active, student-centered approach? What will be the biggest challenges? How will students react? Following are some answers to these questions from my decade of reformed teaching and professional development to help others transform their teaching, as well as resources from researchers and reformers in this field.

"I don't have time"

One of the most common challenges cited by instructors reforming their courses is lack of time: time to find or develop new course materials and time to master new skills and approaches (Krockover *et al*., 2002; Pfund *et al*., 2009; Brownell and Tanner, 2012; Stanulis *et al*., 2016). The CSLC, embedded in backward design, is intended to help instructors save time by avoiding the paralysis that accompanies indecision or lack of direction when developing materials for a new teaching approach. It provides a relatively simple stepwise process for approaching course topics that will become habitual with time and experience. Use of the accompanying decision tree will also save time, because it makes starting from scratch unnecessary. Instructors can use the decision tree to analyze quickly existing materials and either discard or repurpose them. Once the old materials have been given new roles, they can be assigned to different stages of the learning cycle and matched with approaches for introducing students to the material, for example, think–pair–share or brainstorming. When choosing approaches, adapting is quicker than creating, so another time-efficient strategy is to connect with other reformers and share materials or use reformed materials from other resources like the following:

- Science Education Resource Center (http://serc.carleton.edu/index.html)
- Carl Wieman Science Education Initiative (www.cwsei.ubc.ca/index.html)
- Pathways to Scientific Teaching (http://first2.plantbiology.msu.edu/resources/frontiers/scientific_teaching_first.html)
- National Center for Case Study Teaching in Science (http://sciencecases.lib.buffalo.edu/cs)
- CourseSource (www.coursesource.org)

"I'm uncomfortable with the techniques."

Developing materials is only half the battle. Becoming comfortable implementing new approaches in the classroom is the other. Most current science faculty did not receive training in evidence-based teaching as graduate students (Handelsman *et al*., 2004; Ebert-May *et al*., 2011). Even those who take part in professional development early in their careers spent most of their education in lecture-based classes. Relinquishing control, especially after being accustomed to lecturing, can be intimidating. Furthermore, when instructors relinquish control and allow students to engage, learning activities do not necessarily proceed as expected, which can be misinterpreted as failure. Discomfort at the beginning is normal and not grounds for abandoning active, student-centered strategies. As instructors become more comfortable with the role of "guide on the side," their focus begins to shift away from themselves as teachers and toward the students as learners. A vision of learning activities as blank canvases on which students will reveal their thinking, rather than paint-by-numbers pictures that they are expected to complete in a predicted manner, will emerge. In my experience, the transition from a teacher- to a student-centered approach is more subtle and gradual than the transition from passive to active learning. In addition, development of the former tends to lag behind the latter. Rarely have I observed instructors transition from a passive, teacher-centered to an active, student-centered approach in a single step.

"How do I know if I'm doing it right?"

Inflated perceptions of progress in the classroom can hamper reform efforts (Ebert-May *et al*., 2011). Peer review from a colleague or comentor involved in reform fosters development of reflective practices and provides invaluable feedback to push practitioners toward more active, student-centered classes (Hattie and Timperley, 2007; Finkelstein and Fishbach, 2012; Gormally *et al*., 2014). Reviewers can use a simple timing-analysis technique that requires no training to provide an accounting of the amount of time students spend actively engaged with course content (R. Phillis, University of Massachusetts, Amherst, personal communication). During timing analysis, the reviewer keeps track of class time spent in passive or active modes: *passive*—instructor is disseminating information, for example, describing, explaining, giving examples, or setting up an activity, or students are reading, watching video clips or animations; or *active*—instructor is going back and forth with students to ask or answer questions or facilitate a whole-class discussion or students are working individually, in pairs, or in groups to answer a question, solve a problem, or complete a task (Table 3). Data from timing analysis inform instructors about how much time they are spending in a passive mode overall and how long they passively transmit information between learning activities. Delivering complex information for long periods without time for processing can tax student attention and working memory capacity (Hartley and Marshall, 1979; Paas *et al*., 2003). Instructors can use the timing-analysis table to identify sections of class in which learning activities could be inserted to break up long periods of passivity and engage students in processing and using information.

In addition to timing analysis, peer reviewers can use published observation protocols such as the Classroom Observation Protocol for Undergraduate STEM (COPUS; Smith *et al*., 2013) or homemade rubrics to provide a richer picture of the types of activities students are engaged in during class time. Like timing analysis, COPUS is a mirror that will provide an objective reflection of what happens in the classroom so instructors can decide what, if anything, they would like to change. Broadly defined, active learning can encompass any activity where students are cognitively engaged in formulating some form of answer or response. So, while students responding to prompts that require only rote memorization is, technically, active learning,

TABLE 3. This timing-analysis chart with examples in rows 2–5 is a template that can be used by a peer reviewer to calculate the percentage of class time spent in an active-learning mode

Start time	Stop time	Total time	Mode	Description of activity
0:00	0:02	2 minutes	Passive	Instructor presenting learning objectives and reminding students of concepts from previous class
0:02	0:03	1 minute	Passive	Instructor introduces opening topic and question
0:03	0:06	3 minutes	Active	Students brainstorming and reporting out responses
0:06	0:16	10 minutes	Active	Group work and response report out
Total class time		Add all times from this column		
Total active time		Add only active rows from this column		
% Active time		Total active time/total time		

instructors must ask themselves whether this accurately represents the level of cognitive activity required for students to achieve the desired learning outcomes. The following three questions—adapted from a rubric used to evaluate participants of the FIRST IV (J. Momsen, North Dakota State University, personal communication)—simply but effectively target common challenges that instructors face when transitioning to active, student-centered classrooms:

1. Is the instructor doing something that the students should be doing?
2. Do the cognitive levels of the learning activities merit use of class time?
3. How could class be modified to make it more active and/or student-centered?

Feedback from this rubric allows the reviewer to provide constructive feedback about how to modify instruction to make it more active and focused on student learning.

"How will my students respond?"

Students can feel just as uncomfortable as instructors when encountering new teaching methods in the classroom. There are many ways to garner buy-in from students for new approaches (Silverthorn, 2006; Prince and Felder, 2007; Seidel and Tanner, 2013). Seidel and Tanner (2013) reviewed the literature in this field and suggested strategies for preventing student resistance to active-learning classes. One way is to reduce the perceived social distance between instructors and students by doing things like smiling, walking around the room, making eye contact, and learning student names. Another way is to be transparent about the format and rationale for using active learning in the classroom (Felder, 2007). Instructors can free up the first day of class by posting the syllabus online and requiring students to complete a quiz on its most important policies. Students can then spend that first day getting to know their classmates, their teacher, and the class structure (Ebert-May and Hodder, 2008. Instructors can engage students with the "how" and "why" of the course format, using questions such as "What should you be able to do after 4 years of college?" and "What should we do in class to help you get there?" These are ways to get students to explain why they should not simply sit, listen, and memorize in class (Smith, 2008). Engaging students in activities that highlight the difference between knowing and being able to use knowledge can also be very helpful. An excellent example of this strategy is the problem of a general trying to capture a fortress (Gick and Holyoak, 1980), which is highlighted in *How People Learn: Brain, Mind, Experience and School* (NRC, 1999a). I use this on the first day of class to foster student buy-in to active learning (Box 2). When my students process these two scenarios in sequence, they, like the students in the Gick and Holyoak (1980) study, rarely transfer knowledge

BOX 2. An Example of Problem Solving to Foster Buy-In from Students

General's Solution

A general wishes to capture a fortress located in the center of a country. There are many roads radiating outward from the fortress. All have been mined so that, while small groups of men can pass over the roads safely, a large force will detonate the mines. A full-scale direct attack is therefore impossible. The general's solution is to divide his army into small groups, send each group to the head of a different road, and have the groups converge simultaneously on the fortress.

Tumor Radiation Problem

You are a doctor faced with a patient who has a malignant tumor in his stomach. It is impossible to operate on the patient, but unless the tumor is destroyed the patient will die. There is a kind of ray that may be used to destroy the tumor. If the rays reach the tumor all at once and with sufficiently high intensity, the tumor will be destroyed, but surrounding tissue may be damaged as well. At lower intensities the rays are harmless to healthy tissue, but they will not affect the tumor either. What type of procedure might be used to destroy the tumor with the rays and at the same time avoid destroying the healthy tissue?

Example of Use on the First Day of Class

1. Allow students to read the "General's Solution" for capturing the fortress as an example of the type of problem-solving skills they should acquire during the course of their degree.
2. Next, allow them to contemplate the "Tumor Radiation Problem" and ask for a show of hands by those who are confident that they have a workable solution. (I assure them that I will not call on anyone at this point to share his or her solution in order to foster participation.)
3. Reintroduce the "General's Solution" and ask whether there is anything in the first scenario that can help students to find a solution to the second.
4. Finally, ask for another show of hands by those with a solution. Ask for a volunteer to share his or her solution. Compare the number of raised hands before and after to prompt a discussion/reflection on the difference between having and being able to apply knowledge.

Adapted from Box 3.7 of NRC (1999a).

from the first situation to the second without being explicitly prompted to do so. Allowing students to experience this phenomenon for themselves provides a powerful epiphany moment. Consulting educational reports, such as those from the National Academies, or seeking help from educational advisors at institutional teaching centers can be invaluable in finding examples like these to promote student motivation to engage in class learning activities.

"It's a marathon, not a sprint."

The rate of change on any learning curve is slower at the beginning and increases with time. Keeping this in mind fosters a less stressful, long-term vision for classroom reform efforts. Trying to change everything at once can be overwhelming for both the instructor and the students, leading to a negative experience with active learning. Allow sufficient time to develop new materials and skills comfortably by beginning with only one or two new strategies on a regular basis. This allows both the instructor and the students to get accustomed to the new methods. When next teaching the course, the instructor can use existing learning activities and focus on expanding his or her existing toolbox of materials and skills. Students still reap benefits of the incremental increase in active learning as their instructors are climbing the learning curve (Knight and Wood, 2005).

Many factors (e.g., instructor style; class topic, level, and size; and physical and technological aspects of the learning space) contribute to making each classroom unique. As instructors transition to active, student-centered classrooms, they will test, refine, and/or discard strategies and materials as they build unique and varied teaching toolboxes that fit their personal styles and their students' needs. Seeking assistance from external sources and allowing sufficient time for the transition will make the experience much more satisfying. In addition to improving student learning, an unexpected benefit will be that teaching this way is fun.

SUMMARY

Learning cycles have been helping K–12 science teachers create better learning experiences for their students for decades. The CSLC is an adaptation of the successful BSCS 5E learning cycle targeted at college science teachers, in particular, new practitioners of reformed pedagogies. The CSLC retains the first (engage) and last (evaluate) stages of the 5E, both in name and function. The central three stages (explore, explain, elaborate) become a single stage of knowledge construction (construct) that uses deliberate practice to foster acquisition of conceptual understanding and critical-thinking skills during class. When the CSLC is used as the third phase of backward design, condensing the three middle stages offers college instructors greater flexibility in determining the type and order of activities that provide students the experiences needed to successfully achieve the desired course learning outcomes.

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