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Lesson

Exploring Primary Scientific Literature through the Lens of the 5 Core Concepts of Biology

Kyriaki Chatzikyriakidou[1], Chelsey Manrique[1], Marie Janelle Tacloban[1], and Melissa McCartney[1,2]*

[1]STEM Transformation Institute, Florida International University

[2]Department of Biological Sciences, Florida International University

Abstract

Biology students at the undergraduate level usually excel in knowing biological facts; however, they often struggle with connecting these facts to specific biological principles. In parallel, undergraduate students often struggle to read primary scientific literature (PSL), possibly for the same reason: they struggle to integrate the biological facts they know into the larger, and often complicated, biological principles presented in PSL. Our lesson bridges the gap between student understanding of content knowledge and their ability to connect this knowledge to larger biological principles through the integration of PSL and the 5 Core Concepts of Biology (5CCs) identified in the *Vision and Change* report. We begin by introducing students to PSL using a modified C.R.E.A.T.E. method and continue by walking students through *Vision and Change* as a way to introduce the 5CCs. Through the use of a matrix table detailing each one of the 5CCs and their related organizational levels, students learn how to integrate PSL and the 5CCs by connecting biological facts contained within PSL to a related biological core concept. Because students have to provide reasoning for why they connected a biological fact to a specific core concept, they begin to see biology as a larger entity, i.e., they begin to see the "big picture" of biology. Our lesson provides a novel strategy for introducing students to PSL.

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Supporting Materials: Supporting Files S1. Exploring Primary Scientific Literature – Blank 5CCs Matrix table; S2. Exploring Primary Scientific Literature – example syllabus; S3. Exploring Primary Scientific Literature – Slides for introducing the 5CCs; S4. Exploring Primary Scientific Literature – Slides for introducing PSL; S5. Exploring Primary Scientific Literature – example exam; and S6. Exploring Primary Scientific Literature – exam grading rubric.

***Correspondence to:** mmccartn@fiu.edu; 11200 SW 8th Street, Miami, Florida 33199.

Learning Goal

Students should be able to interact differently with PSL after learning how to use the 5CCs matrix table.

Learning Objective

Students should be able to find examples of the 5CCs within the text of a piece of PSL.

INTRODUCTION

A successful science education includes teaching students science process skills such as critical analysis of primary scientific literature (PSL) (1,2). This is a fundamental skill for practicing scientists; however most college science departments lack a formalized curriculum for teaching undergraduates how to read, interpret, and discuss PSL (3-5). Instead, the use of PSL in the classroom remains limited due to several barriers, including students struggling with the actual practice of science (as opposed to the purely linear scientific method presented in textbooks), scientific jargon, and an inability to connect PSL to the broader context of the discipline (6-8). Additionally, most novice students are still developing the critical thinking skills needed to interpret the results and conclusions found in PSL. To complicate matters, some educators may be uncomfortable using PSL themselves, due to concerns about student pushback or their sense that the material is too complex for their students (9,10).

Despite these barriers, a growing body of literature shows that PSL is a valuable and useful tool for STEM education. For example, closely analyzing PSL in a classroom setting engages students in discussion and debate around interpretations of experimental data while building their insight into scientific practices (11). Teaching with scientific research papers has been shown to promote critical thinking, experimental design ability, and epistemological maturation as well as to improve students' positive attitudes about science and scientists in both two-year and four-year settings with first-year as well as upper-level students (12-17). PSL can also show students that even after a study is completed and published, there are still many unanswered questions for future scientists, promoting the development of creativity through study design assignments (3,11).

Published examples of PSL-based research show PSL being used by educators at all levels, highlighting the diversity, scalability, and flexibility of PSL as an educational tool. Programs include journal clubs, data and figure exploration, tutorials on how to read PSL, annotated literature, and full courses being taught only with primary literature (5,11,14,18,19). Assessment tools used to evaluate these programs are equally as diverse, ranging from rubric to validated survey (20,21).

We are interested in introducing Introductory Biology students to PSL. While undergraduate biology students usually excel in knowing facts about biology, they struggle with connecting these facts to specific biological principles (4,22). We hypothesized that we would be able to integrate PSL and biological principles together, as a way to both introduce students to PSL and to encourage students to start thinking about biology less as a set of facts and more as a set of principles.

To do this, we developed an interactive classroom activity (summarized in Table 1) designed to introduce students to PSL using the Five Core Concepts of Biology (5CCs) described in *Vision and Change* (1,23). The 5CCs provide a detailed and content-based description of the knowledge of biology, summarized in five core biology concepts that dictate natural biological phenomena or processes (evolution; structure and function; information flow, exchange, and storage; pathways of transformations of energy and matter; and systems) connecting to five main biological scales (molecular, cellular, organismal, populational, and ecological) (Table 2). Understanding that every biological process or phenomenon can be analyzed into five different perspectives, as suggested by the 5CCs, is fundamental for understanding that biological facts link to concepts and that concepts link to other biological concepts (1). Using the 5CCs, we developed a matrix table with five rows, each containing a core concept and three columns, each containing a biological scale (for simplicity, we only use three biological scale levels, merging molecular/cellular to one scale, using organismal as the second scale, and merging population/ecology for the third scale) (an example 5CCs matrix table is shown in Supporting File S1. Exploring Primary Scientific Literature – Blank 5CCs Matrix table. Students were asked to fill in the matrix table as they read a selected piece of PSL as a way to encourage them to begin to think of scientific facts contained within PSL as part of larger biological concepts.

Intended Audience

This activity was used with students enrolled in “Essentials of Biology,” an introductory biology course centered on reading PSL. The course was designed to introduce introductory students to the five core concepts of biology, along with critical thinking, analysis, and experimental design, through reading PSL. Over the course of the semester, students read 14 pieces of PSL accompanied by class discussions, active learning modules, accompanying worksheets, and homework assignments designed to show students that PSL is the global language of scientists, and that being able to deconstruct PSL is a valuable skill to have as a future scientist. The 5CCs matrix chart described here (Supporting File S1. Exploring Primary Scientific Literature – Blank 5CCs Matrix table) was implemented 14 times within this course.

Three offerings of “Essentials of Biology” had class sizes of *n*=32 (Fall 2018), *n*=11 (Spring 2019), and *n*=25 (Fall 2019, described in this manuscript). Collectively, the student demographics for these three offerings were 63% female; 74% Hispanic/Latino, 14% Black or African American, 7% White, and 4% two or more races; 45% freshman, 23% sophomores, 16% juniors, and 10% seniors; and 63% biology majors. While we have not yet implemented the 5CCs matrix charts into upper-level lecture or lab courses, we have no reason to believe they couldn’t be implemented with more advanced students.

We implemented the 5CCs matrix charts at Florida International University, a public Carnegie R1-ranked urban university and a Hispanic Serving Institution, enrolling 41,794 undergraduates in Fall 2019, of which 67% were Hispanic/Latino, 12% were African American/Black, and 57% were women. The biology major had 4,159 students enrolled, composed mostly of Hispanic students and large numbers of First Generation (~20%) and Pell-eligible students (~51%).

Required Learning Time

The 5CCs matrix chart activity described here is designed to fit into a 50-minute class period. However, we implemented this activity several times over a semester long course, essentially using this 50 minute stand-alone activity repeatedly with each piece of PSL read in class (Supporting File S2. Exploring Primary Scientific Literature – example syllabus). While we used the 5CCs matrix chart 14 times over the course of the semester, we imagine different student populations and classroom environments would still benefit using this activity as a stand-alone or in a different variation of repetition. The amount of time needed to introduce students to both the 5CCs and PSL will vary, and there is more than one way for this to occur. We detail what has worked for us below.

Prerequisite Student Knowledge

This 5CCs matrix chart is intended for use at any point in the semester after students have received a basic introduction to the 5CCs. The 5CCs are described in detail in *Vision and Change* (Table 2) and in the BioCore Guide (1,23). In our experience, students should be able to define the 5CCs in their own words and understand the different scales of the 5CCs. We spend two class sessions on this prior to using the 5CCs matrix charts (Supporting File S2. Exploring Primary Scientific Literature – example syllabus, Supporting File S3. Exploring Primary Scientific Literature – Slides for introducing the 5CCs), however there is more than one way to introduce students to the 5CCs and instructors are encouraged to find a method that works for them. Frameworks, rubrics, assessments, and additional resources for implementing the 5CCs have been summarized in a recent essay which will be helpful for instructors less familiar with the 5CCs (24).

To introduce the 5CCs to our students, we start by explaining the *Vision and Change* meeting itself, describing how 500 biology educators sat in the same room for two days discussing what is truly essential in biology education. We ask them to envision just the students in the room distilling biology down to only 5 concepts, extrapolating to what it must have been like to go through this with 500 biology experts. Anecdotally, this discussion instills in the students a sense that what they are about to learn was debated and decided upon democratically by experts, and therefore it must be very important.

Instead of simply showing the students a list of the 5CCs, we provide an image representing each of the 5CCs and encourage a class discussion on what it could be (Supporting File S3. Exploring Primary Scientific Literature – Slides for introducing the 5CCs). Again, anecdotally, we have found that the students become more invested in learning about the 5CCs when they are allowed to "discover" them, rather than simply being told what they are.

Once each of the 5CCs has been identified, we lead a discussion around additional examples for each of the 5CCs that the students come up with by themselves. We place a strong emphasis here on how there can be more than one "correct" answer, which will come up in all future think-pair-share and group discussions relating to the matrix charts.

Students should also be comfortable reading a piece of PSL. In our experience, introductory students have a general idea of what PSL is, and some have prior experience with reading PSL, however they do not reflect positively on these experiences. We spend two class periods discussing PSL in general (Supporting File S2. Exploring Primary Scientific Literature – example syllabus). We bring old copies of *Science* and pass them out to students, each student with their own copy. Together, we flip through each page of *Science* and have a general discussion on the goals of each section, the audience for each section, and who develops content for each section (example discussion prompts include: What is the purpose of this section? Who writes this section? Are they a journalist or a scientist? What is the audience for this section? Do you find this section interesting? Do you find this section easy to read? Do you trust the person who wrote this?). These discussions are different with each group of students and therefore we are unable to provide detailed instructions on how to replicate this. In our experience, very few students have ever sat and looked through a scientific journal page by page, and this exercise provides an overview of PSL without actually reading any PSL, ultimately helping students to be more open to reading PSL.

Next, we use a modified version of C.R.E.A.T.E. (Consider, Read, Elucidate hypotheses, Analyze and interpret data, Think of the next Experiment) to introduce students to PSL (11,12; https://teachcreate.org/). C.R.E.A.T.E. is an evidence-based strategy that can be tailored to individual instructors and student populations. Instructors wanting to implement C.R.E.A.T.E. are encouraged to visit the "literature section" of the C.R.E.A.T.E. website to learn more about the research behind the C.R.E.A.T.E method (https://teachcreate.org/literature/). Examples of how other instructors have implemented C.R.E.A.T.E. can be found in the searchable database of "road maps" available (https://teachcreate.org/roadmaps/). Our modified implementation consists of using several pieces of stand-alone PSL instead of the four connected papers suggested by the C.R.E.A.T.E. method. Additionally, we limit our C.R.E.A.T.E. activities to cartooning the abstract, re-writing the title, defining unfamiliar words, and identifying the hypothesis being tested or question being addressed (12). While this adapted C.R.E.A.T.E method works for our course and our student population, it is possible for instructors to introduce students to PSL using other methods.

We use "Empathy and Pro-Social Behavior in Rats" as our introduction to reading PSL and work through the C.R.E.A.T.E. exercises of breaking down the title, cartooning the abstract, and predicting the next experiment (Table 3, Supporting File S2. Exploring Primary Scientific Literature – example syllabus, Supporting File S4. Exploring Primary Scientific Literature – Slides for introducing PSL). "Empathy and Pro-Social Behavior in Rats" does not contain large amounts of jargon and the experimental design is beautifully simple, allowing for students to really get into how and why the authors designed these experiments and the larger biological concepts involved. Depending on the response of the students, we work through 2-3 more pieces of PSL using modified C.R.E.A.T.E. (Table 3).

Prerequisite Teacher Knowledge

The instructor should have some familiarity with the 5CCs described in the *Vision and Change* report (1,23). For instructors wanting to learn more about the 5CCs, additional frameworks, rubrics, assessments, and other resources for implementing the 5CCs have been summarized in a recent essay (24). If an instructor is unfamiliar with the 5CCs we do not recommend implementing this activity.

The instructor should be comfortable reading PSL themselves and should be able to identify pieces of PSL that are at the appropriate level for their students. There is no easy method for selecting appropriate PSL for a given population of students. Finding appropriate PSL takes time and effort and, based on content to be covered and student knowledge levels, may need to be adapted each time the course is implemented. When considering a new piece of PSL, we first ask our Learning Assistants and undergraduate research assistants, who are closer to our student population with regard to content knowledge and vocabulary level, to read the PSL and give us their feedback. This has been a successful "first round" screening for us. We have listed the PSL we used in the fall semester of 2019, and given a brief reason why we used each piece, in Table 3. The majority of PSL used in our class is also available as annotated versions on the Science in the Classroom website (https://www.scienceintheclassroom.org/), a collection of annotated PSL that has been carefully selected to 1) be accessible to an introductory-level undergraduate and 2) be cutting edge, novel science. This resource is easily searchable and may be useful for instructors as they decide which PSL to select for their class. Additionally, annotated PSL can be used as an alternative method to C.R.E.A.T.E. for introducing PSL to students (19). If instructors are not comfortable reading PSL, or are unable to find PSL at the appropriate level for their students, we do not recommend implementing this activity.

SCIENTIFIC TEACHING THEMES

Active Learning

The activity includes a 5CCs matrix chart for students to complete on their own as they read a piece of PSL (Supporting File S1. Exploring Primary Scientific Literature – Blank 5CCs Matrix table). Recent research has shown that the addition of worksheets (5CCs matrix charts) as an active learning tool for in-class group activities promotes student collaboration and develops problem solving skills (25). We complement our matrix charts with think-pair-share (26) and whole class discussions. We start with think-pair-share as a way for students to "vet" their answers within a small group and to alleviate possible anxiety of speaking in front of the whole class. During this activity, we ask students to notice that their matrix chart might look completely different than their partners, yet both matrix charts can be correct. We ask students to share their reasoning for placing an answer in a certain box with their partners. While we have only anecdotal data, we do hear argumentation taking place during this activity as students explain their reasoning to their partner.

In whole class discussions, volunteers are encouraged to share their matrix charts with the whole class while the instructor facilitates moving the conversation from student to student. Because there is often more than one “correct” answer per matrix chart box, other students may support or disagree, generating an active discourse across the class. This is the same discussion that takes place during the one-on-one sharing (i.e., students are presenting their reason for putting an answer in a certain box to the rest of the class). More than one “correct” answer is often a new concept for our students, making instructor facilitation of these conversations a critical part of their success. Anecdotally, while we do not often have students disagreeing with the presented answer, we do have students acknowledging that their classmates’ reasoning helped them to see either a 5CC or content contained within PSL in a new light.

The first implementation of this course took place in an active learning classroom where each student desk was on wheels and easily movable. In this setting, we were able to easily assign students to groups and have students move around the room, ensuring that they were often working with different partners. In the second implementation students sat in rows of tables, which made switching of groups difficult and students most often just worked with their neighbor. The third implementation used stationary desks that were somewhat moveable, allowing for more interaction among students than the rows of tables, but much less than the active learning classroom. While we did our best to regularly change student groups, we were not always successful. Most often, students started an activity alone, then paired with a partner for a first round of discussion, and then joined a larger group of four students for a second discussion.

Assessment

Assessment of student understanding comes from scoring the matrix tables. While we looked at matrix tables throughout the semester, by discussing them in class and having students work with a partner to compare/contrast their own answers, we only graded matrix tables completed as part of an exam. Our exams consisted of the full piece of PSL printed out and given to each student so they could write and take notes as they read. Students were given a printed exam containing a blank matrix chart (Supporting File S5. Exploring Primary Scientific Literature – example exam) and a printed copy of the piece of PSL (Table 3). We developed a rubric for each piece of PSL used for an exam, trained Learning Assistants and undergraduate research assistants on how to use the rubric, and worked as a team to grade matrix charts (Supporting File S6. Exploring Primary Scientific Literature – exam grading rubric). A sentence describing the connection between a piece of information from the given PSL and a core concept (connected to the correct biological scale), and the reasoning students used to get there, would typically receive full credit. Figure 1 shows four examples of completed matrix charts from an exam. We provide this figure as an example of 1) how students complete the 5CCs matrix chart and 2) and example of the variation among student answers for the same piece of PSL.

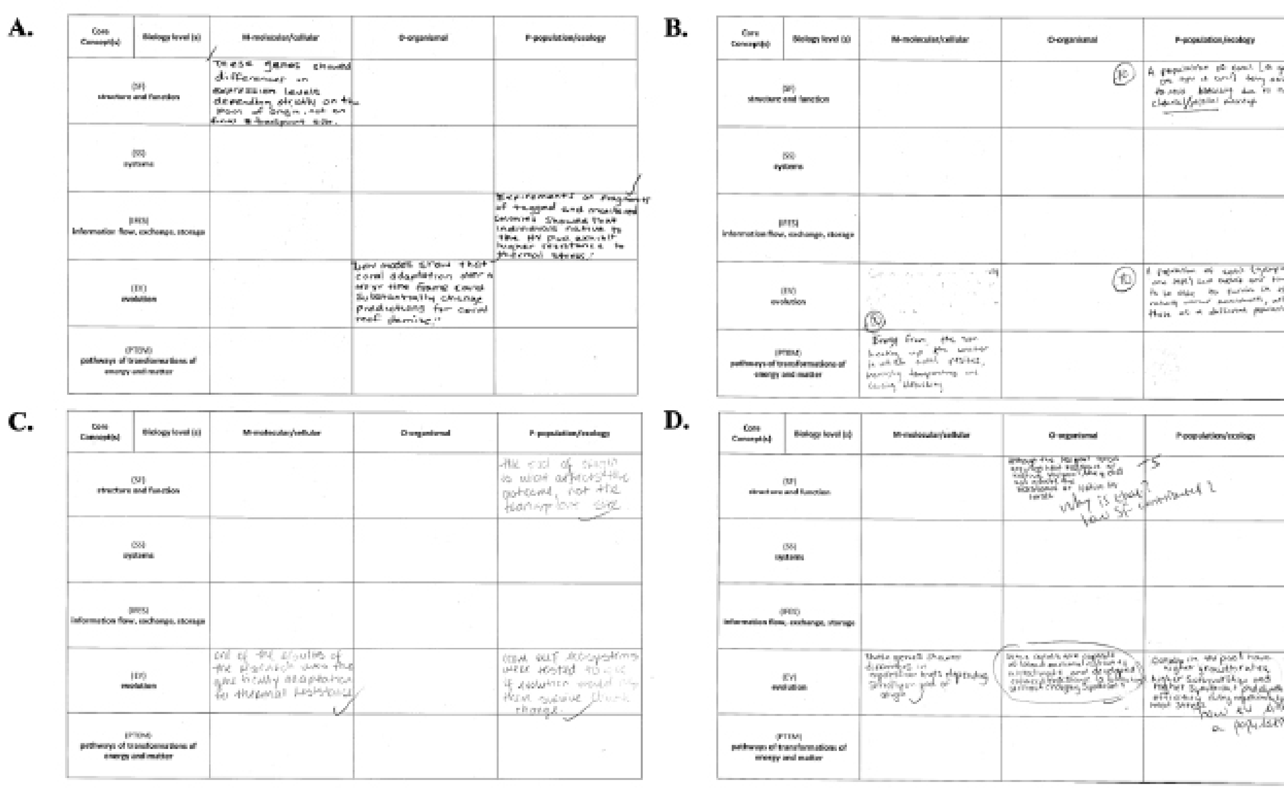

Figure 1. Examples of complete (A, B, C) and incomplete (D) student responses to placing concepts discussed in PSL into a 5CCs matrix chart. The responses have been graded by the research team. Instructions to students were as follows: “From the information presented in the paper “Mechanisms of reef coral resistance to future climate change” fill in three boxes in the chart below. Make sure to fully describe why you chose each box (30 points)” (Supporting File S5. Exploring Primary Scientific Literature - example exam). A grading rubric is shown in Supporting File S6. Exploring Primary Scientific Literature - exam grading rubric. We provide this figure as an example of 1) how students complete the 5CCs matrix chart and 2) the variation among student answers for the same piece of PSL.

We provide student feedback in Table 4 to highlight student responses to our activity. Specifically, we show that our Learning Goal of "Students should be able to interact differently with PSL after learning how to use the 5CCs matrix table" has been achieved with the following student responses:

- *"In future science courses, I will use the skill of breaking down the core concepts of biology...."*
- *"In all my future biology classes or careers, I think the thing I will remember most is to break down the article using the 5 cc's..."*

We also see evidence that our hypothesis of being able to integrate PSL and biological principles together, as a way to both introduce students to PSL and to encourage students to start thinking about biology less as a set of facts and more of a set of principles, i.e., the big picture, is plausible, as shown in the following student responses:

- *"Thinking about the bigger picture in the topics I learn."*
- *"Understanding the bigger picture of why biological experiments are being conducted."*
- *"...this class really helped with the understanding of biological concepts."*

Additional student responses also suggest that students are becoming more comfortable reading PSL (*"That there is no paper that I can NOT understand..."*), are interacting differently with PSL after learning how to use the 5CCs matrix table (*"... this class has opened my eyes to a more interactive and simpler way of braking down harsh topics..."*), and are able to connect the 5CCs and PSL (*"...I will use the skill of breaking down the core concepts of biology, and using it to see how it'll apply to specific research study..."*). We have bolded, italicized, and underlined specific student examples showing this (Table 4).

Inclusive Teaching

Reading carefully selected PSL has the potential to engage many individuals, since questions about authentic scientific studies are typically very interesting to most students. This lesson seeks to create a learning environment where students' academic, social, and cultural backgrounds can be an asset to their learning. Because there can be a variety of responses in each matrix box, all student viewpoints and conclusions can be included in class discussions.

The majority of class discussions occurred in small groups, often with the same students, resulting in students becoming comfortable enough to share their answers freely. Additionally, because there was more than one "correct" answer for each matrix table, it became easier for students to share their answers without the fear of being wrong. However, for the larger group discussions, we asked for volunteers and did not force students to address the class if they did not volunteer.

LESSON PLAN

At this point, students should be comfortable with both the 5CCs and PSL. This activity, which is specifically using a 5CCs matrix chart to guide students reading a piece of PSL, is designed for a 50-minute class period after students have been introduced to the 5CCs and to reading a piece of PSL. In our course, we implement this 50- minute activity 14 times over one semester. Table 1 shows the teaching timeline for the activity.

To introduce the matrix charts to the students, show example matrix charts (one PowerPoint slide of 4 different matrix charts all filled in differently and all receiving full credit, similar to what is shown in Figure 1). Stress that students need to be able to explain why they chose a certain concept and organizational level and show a successful argument (e.g., for transformation of energy: energy from the sun allows for photosynthesis) versus a generic answer (e.g., energy moves through the system). During class discussions, also strive for this kind of detailed explanation: the student reasoning for why the answer goes in the box must be there. Discussion prompts for class discussion include: What is the structure? What is the function? What is the information? Where is the information stored? Where is the information flowing? How is the information flowing? What is the energy? What is the matter?

It is important to note that students are only required to fill in 3 boxes of the matrix chart. Do not specify that there must be one box per 5CC, or one box per organizational level; simply ask for 3 boxes in total. It is unrealistic for PSL to connect to each 5CC at three different levels, for a total of 15 connections. We settled on three as a compromise between 1) content contained in PSL, 2) student level of understanding of both 5CCs and PSL, and 3) time available for the activity. In our experience, students excel in filling in a wide array of boxes across the matrix chart; we rarely see three answers in the same concept or organizational level.

Start this activity with a paper you used in the introduction to PSL section (e.g., return to "Empathy and Pro-Social Behavior in Rats"), as students are already familiar with this piece of PSL, and they can just focus on learning how to connect the biological facts found within the paper to the larger biological concepts of the matrix table. Print out copies of the 5CCs matrix table to hand out to each student (each student has their own copy) so students are able to take notes and write answers directly onto the chart itself. Work through this first chart together, first with think-pair-share and then a larger group discussion. During both types of discussions, continuously stress that there is more than one "correct" answer, but students need to be able to explain why they put a certain fact from the PSL into a specific matrix box. Ask students "why that box? why that level?" whenever possible. Next, assign each small group another piece of PSL that they have already worked through using C.R.E.A.T.E. Task them with completing a 5CCs matrix chart that they will then present to the larger group. Continue in each subsequent class period to assign additional pieces of PSL and 5CCs matrix charts as homework (we work through one piece of PSL at a time) and continue to read additional PSL, with accompanying 5CCs matrix charts, together in class (Supporting File S2. Exploring Primary Scientific Literature – example syllabus). Generally, we recommend reading one piece of PSL per class; however, some pieces of PSL that you wish to spend more time on can be spread out over two class meetings. In our experience, students have given feedback on what papers they read through quickly and lose interest in (Table 3, PSL #2 and 4) and what papers catch their attention and keep them wanting more discussion (Table 3, PSL # 7, 10, and 11). We anticipate that any instructors implementing this activity will receive similar feedback from their own students.

Example Matrix Templates

Develop a rubric for each PSL (Supporting File S6. Exploring Primary Scientific Literature – exam grading rubric).Learning Assistants, Teaching Assistants, and Undergrad Research Assistants can be trained to help assess 5CCs matrix charts. It is helpful to assess the matrix charts together so questions can be asked about individual responses and any rubric clarifications can be addressed. Example matrix charts are shown in Figure 1 as example of how an average student in our course completes the chart.

TEACHING DISCUSSION

Reactions from Students

We collected qualitative data from students on their perceptions of the course as part of the final exam. Representative answers are shown in Table 4. In general, students indicate that they have made the connection between using the 5CCs to make PSL easier to understand and to see the "big picture" of biology. We are currently working on developing a more quantitative way to measure student gains using the 5CCs matrix charts.

Persistent Conceptual Difficulties

Some common issues we have seen across all three semesters include:

- Structure and function is traditionally the hardest one of the 5CCs for students to grasp. We have found that asking the students to explain "what is the structure and what is the function," and encouraging them to be as specific as they can, helps with student understanding.
- Evolution and reproduction are not the same thing. Students often confuse these concepts when arguing for placing content in the Evolution boxes.
- We receive a lot of "generic" reasoning for picking Pathways of Transformation of Energy and Matter and Information Flow, Exchange, and Storage. Our students struggle to identify the type of energy and matter, or the type of information, involved. We have started to require students to identify the type of energy and matter, or the type of information, in these matrix boxes to receive full credit.

Extensions to the Lesson

It is possible to add a backside to the 5CCs matrix chart consisting of the 6 core competencies described in Vision and Change (Supporting File S1. Exploring Primary Scientific Literature – Blank 5CCs Matrix table). This backside of the chart can be used in the same way as the 5CCs side, asking students to connect parts of the PSL they are reading to each competency. In our experience, including these competencies adds more of a "human face" to PSL. Additionally, this version of the matrix chart can encourage career exploration with discussions of "the ability to tap into the interdisciplinary nature of science" and "the ability to communicate and collaborate with other disciplines."

Passages from textbooks can also be used with the 5CCs matrix. During our third implementation of this course, as part of an exam, we provided sample text from an introductory biology textbook used at our university. We conferred with introductory biology instructors at our institution and asked them which topics students seemed to struggle with the most. Based on their replies, we identified sections of the introductory biology textbook (usually 2-3 paragraphs) on these topics and included this text on the third exam. We asked students to evaluate this text using the same matrix chart that they were using for the PSL. The idea was to show students that if/when they go on to introductory biology and are confused with the dense readings in the textbook (or a likely topic they might struggle with), they can apply the 5CCs to help with understanding.

Conclusions

As discussed in the introduction, there are many different ways to use PSL as a teaching and learning tool and combining the 5CCs with PSL can lead to multiple different teaching approaches. Our activity is novel and at the same time very basic, so it could be easily adapted for a plethora of class sizes and course levels. According to our knowledge, this is the first PSL activity designed to encourage students to connect the biological facts they read about to the larger concepts of biology. Our initial data collection suggests that students are beginning to see biology as a larger entity (i.e., they begin to see the "big picture" of biology). We are just beginning to explore how to use the 5CCs as a learning framework, but we believe that our combined 5CCs/PSL activity is an important step in uncovering best practices on how to do this.

SUPPORTING MATERIALS

- Supporting File S1. Exploring Primary Scientific Literature – Blank 5CCs Matrix table.
- Supporting File S2. Exploring Primary Scientific Literature – example syllabus.
- Supporting File S3. Exploring Primary Scientific Literature – Slides for introducing the 5CCs.
- Supporting File S4. Exploring Primary Scientific Literature – Slides for introducing PSL.
- Supporting File S5. Exploring Primary Scientific Literature – example exam.
- Supporting File S6. Exploring Primary Scientific Literature – exam grading rubric.

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Table 1. Teaching timeline for connecting the 5 Core Concepts of Biology (5CCs) and Primary Scientific Literature (PSL).

Description	Estimated Time	Notes
Activity: Connect 5CCs and PSL. One 50 minute class session repeated as necessary throughout the semester		
Welcome/announcements	5 minutes	We recommend starting this activity with a paper you used in the introduction to PSL section. The students will already be familiar with the content. Table 2 shows a list of PSL that has worked in our course. Figure 1 shows example charts from our students.
Instruct students to read a paper copy of PSL and take notes and/or look up information. Expect students to have a general idea of the research study at this point but do not look for complete comprehension.	5-10 minutes	
Give students a blank 5CCs matrix chart to fill out on their own.	5 minutes	Supporting File S1. Exploring Primary Scientific Literature – Blank 5CCs Matrix table.
Direct students to work in pairs or small groups to discuss/compare/contrast their 5CCs matrix charts.	10 minutes	
Lead a whole class discussion on the 5CCs matrix charts. Ask students "why that box?" and "why that level?" Students themselves can lead these discussions with their own questions.	10 minutes	
This time is spent going into detail of a certain section of the PSL. For example go over one of the figures, discuss why the data was presented the way it was (ask students to identify the dependent/independent variable), ask students to describe how the data was collected, or ask students what research question was being answered with the data. Students are usually much more engaged/responsive to this kind of detailed discussion after the 5CC activity, as they have more confidence in reading the paper.	10 minutes	

Table 2. The 5 Core Concepts of Biology as described in *Vision and Change* (1).

Core Concept	Main Description	Importance in Biology
Evolution (EV)	The diversity of life evolved over time by processes of mutation, selection, and genetic change.	Principles of evolution help promote an understanding of natural selection and genetic drift and their contribution to the diversity and history of life on Earth.
Structure and function (SF)	Basic units of structure define the function of all living things.	Structural complexity, together with the information it provides, is built upon combinations of subunits that drive increasingly diverse and dynamic physiological responses in living organisms.
Pathways and transformation of energy and matter (PTEM)	Biological systems grow and change by processes based upon chemical transformation pathways and are governed by the laws of thermodynamics.	An understanding of kinetics and the energy requirements of maintaining a dynamic steady state is needed to understand how living systems operate, how they maintain orderly structure and function, and how the laws of physics and chemistry underlie such processes as metabolic pathways, membrane dynamics, homeostasis, and nutrient cycling in ecosystems.
Information flow, exchange, and storage (IFES)	The growth and behavior of organisms are activated through the expression of genetic information in context.	From gene expression networks to endocrine mechanisms for physiological regulation, and from signal transduction and cellular homeostasis to biogeochemical cycling, all may be understood in terms of the storage, transmission, and utilization of biological information.
Systems (SS)	Living systems are interconnected and interacting.	Mathematical and computational tools and theories grounded in the physical sciences enable biologists to discover patterns and construct predictive models that inform our understanding of biological processes. Through these models, researchers seek to relate the dynamic interactions of components at one level of biological organization to the functional properties that emerge at higher organizational levels.

Table 3. A collection of PSL we have successfully used with introductory biology students as part of "Essentials of Biology." The abbreviations for the 5CCs are as follows: Structure and Function (S/F); Systems (SS); Information Flow, Exchange, Storage (IFES); Evolution (EV); Pathways of Transformations of Energy and Matter (PTEM).

	Piece of PSL (POPSL)	"Main" 5 CCs	Why this POPSL was selected	Use in class
1	Empathy and pro-social behavior in rats. Ben-Ami et al. Science (2011) 334: 1427-1430.	N/A	One of the authors attended a C.R.E.A.T.E. workshop where this POPSL is used in training examples. We replicated C.R.E.A.T.E. training directly here.	Introduction to PSL using the C.R.E.A.T.E. method.
2	Rapid evolution of a native species following invasion by a congener. Stuart et al. Science (2014) 346: 463-466.	N/A	This POPSL has a simplistically beautiful experimental design and the vocabulary is basic, allowing students to start with a POPSL that did not overwhelm them and enabled them to understand the experimental design. As we are located in FL, it grabbed student's attention for being relevant.	
3	An emerging disease causes regional population collapse of a common north American Bat Species. Frick et al. Science (2010) 329: 679-682.	N/A	The experimental design is simple in this POPSL, and is an example of an observational study. We did not get into the data analysis specifically with this POPSL as it is complex. This POPSL was also used to introduce the relevance of science and society, as students were able to grasp the magnitude of species extinction.	
4	Plastic waste inputs from land into the ocean. Jambeck et al. Science (2015) 347: 768-771.	SS	This POPSL has a simple experimental design, basic vocabulary, and is relevant to students' lives. It is also an example of systems at ecology/population scale, how an activity in one part of the globe will ultimately affect everyone.	Active learning and 5CCs matrix chart activities during class.
5	A global mass budget for positively buoyant macroplastic debris in the ocean. Lebreton et al. Scientific Reports (2019) 9:12922.	SS	This POPSL continues work done in #4. We used this POPSL to specifically get into methods of how scientists collect this kind of data (collecting garbage and analyzing it in a lab). In our experience, most students have never connected a piece of data back to the specific person who collected it and followed through on analysis.	
6	The shocking predatory strike of the electric eel. Catania. Science (2014) 346: 1231-1234.	SF	In our experience, S/F was the 5CC students struggled most with, and this POPSL provides a simple S/F experiment with a simple experimental design.	
7	Gut Microbiota from Twins Discordant for Obesity Modulate Metabolism in Mice. Ridaura et al. Science (2013) 341: 1241214-1-1241214-9.	SF PTEM	The experimental design in this POPSL (fecal transplant) grabbed student's attention, and they really engaged. We also used this POPSL as a way to discuss model organisms and why they are necessary/important to science. We started this POPSL with a focus on S/F and used it to transition into PTEM.	
8	Wireless Solar Water Splitting Using Silicon-Based Semiconductors and Earth-Abundant Catalysts. Reece et al. Science (2011) 334: 645-648.	PTEM	While the vocabulary and methods in this POPSL are complex, students were able to understand the basic experimental design of trying to reproduce photosynthesis in a lab. We found that when students finished this POPSL they were proud of having read it and felt more confident in their ability to read PSL on their own.	
9	Polarized notum Activation at Wounds Inhibits Wnt Function to Promote Planarian Head Regeneration. Petersen et al. Science (2011) 332: 852-855.	IFES	Students loved the idea of cutting off a head and watching it grow back! While the signaling pathways in the paper are complex, students were able to understand the experimental design in determining how gene expression and signaling pathways are investigated by scientists.	
10	Sexual Deprivation Increases Ethanol Intake in Drosophila. Shohat-Ophir et al. Science (2012) 335:1351-1354.	IFES E	Alcohol and sex are topics that grab students' attention. We started this POPSL as IFES and used it to transition to EV.	
11	A bacterium that degrades and assimilates poly(ethylene terephthalate). Yoshida et al. Science (2016) 351: 1196-1199.	EV	This POPSL has a simple experimental design. We spent time getting into the methods of how data in this study were collected and discussed how the dataset shown is not as encouraging as it seems at first. We also had a spirited debate on whether this is a promising solution to plastic waste.	
12	Mechanisms of reef coral resistance to future climate change. Palumbi et al. Science (2014) 344: 895-898.	N/A	In our experience, students were anxious to read a POPSL on their own in a limited amount of time during an exam. To alleviate this concern, we selected POPSL with clear experimental design, vocabulary at the students' level, and a length that students can read within an hour. This approach worked for us, as most students could easily finish within an hour and student anxiety comments dropped off significantly after the first exam.	Exam 1
13	The great Atlantic Sargassum belt. Wang et al. Science (2019) 365: 83–87.	N/A		Exam 2
14	Molecular basis for the nerve dependence of limb regeneration in an adult vertebrate. Brockes et al. Science (2007) 318: 772-777.	N/A		Exam 3

Table 4. Representative student perceptions of the course. Student responses connecting to the Learning Objective and Learning Goal of this activity are emphasized in bold, underlined, italic text.

Prompt	Student response
What part(s) of this course do you think you will use infuture science classes?	"Thinking about ***the bigger picture in the topics I learn***."
	"In future science courses, ***I will use the skill of breaking down the core concepts of biology***, and using it to see how it'll apply to specific research study. It'll help me get a sense of what the research Question is really about."
	"In all my future biology classes or careers, ***I think the thing I will remember most is to break down the article using the 5 cc's*** and even draw a picture of the abstract if I can to help me understand it better. It sounds so simple but has proven to be helpful."
How do you view science differently after your experience in this course?	"I have always had a love for science but have been intimidated by college-level classes and methods, but seeing the way ***this class has opened my eyes to a more interactive and simpler way of braking down harsh topics*** has lead me to like science even more."
	"Science is less boring in some subjects ***because I can figure out what research papers are saying better than before***. When you don't understand something it seems less important to you and frustrating and you care less about it. Now that I know how to read primary and secondary research I can understand what is going on and have fun with the different topics in science."
	"The main thing about science that I now view differently is that for many topics there does not need to be one correct answer. Science is fun because of the fact that you can critically think and have different answers/explanations than your peers but still be correct. Rather than Math where there really is only one answer depending on the problem, ***this course has allowed be to see that science can be interpreted in many ways with many different explanations that make sense***."
How did taking this course make you a better biology major?	"***Understanding the bigger picture*** of why biological experiments are being conducted."
	"It taught me the main aspects of biology. I haven't taken any bio course prior to this one. Therefore, I was given a good foundation on what I expect to learn in the further. ***It'll make it easier for me to understand the concepts***."
	"This course helped me realize that there is biology in everything. Scientists aren't strictly lab-based or in academia. Scientists also aren't rigid and stuck in the facts. To be a scientist, you need to be creative and openminded. You need to get out into your field, making observations and sharing data. ***This course helped me understand how to cut through the formulaic academic writing style of research papers and efficiently access the essentials of the paper topic***. I learned to understand the applications of scientific research across multiple disciplines, how a discovery in biology may affect a small business owner or a politician running for office. Everything is related to one another."
What is the main thing you learned in this class this semester?	"***That there is no paper that I can NOT understand***, it just takes patience and using all of the concepts we learned this semester to gain an understanding of the abstract, the information in the graphs and analyzing the different models that may have been used. With all this combined, it will make researching so much easier!"
	"In the beginning of the semester, I was certain that I wasn't going to be able to understand a scientific journal. Now I am. This taught me that anything can be learned, and ***it gave me a lot of motivation and confidence for the future***."
	"Ask questions, read slowly and true science is not about a black and white, right or wrong answer. ***It's about understanding what is known (or believed to be known so far) and then asking questions*** from that to better learn the world around us."
What surprised you the most about this class?	"Coming into the class I thought it was a biology class with a book to study and learn but ***this class really helped with the understanding of biological concepts***."
	"***That reading articles does not have to be so painful!***"
	"What surprised me the most is ***how fast I developed my skill of reading research articles***. Once I got the hang of it and did the various exercises, I very quickly became more confident in understanding the data, research methods, and conclusions the researchers made."