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Lesson

Exploring the Complexities of Photosynthesis Through a Comic Strip

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Abstract

Photosynthesis is a conceptually challenging topic. The small scale at which photosynthesis takes place makes it difficult for students to visualize what is occurring, and students are often overwhelmed by all of the details of the process. This activity uses a freely-available comic to make learning photosynthesis more approachable and to help students identify their own misconceptions and questions about the process. This activity is appropriate for any college-level introductory biology course and although it was designed for an online class, it could be adapted for in-person learning. In this activity, students work through a four-part online module. Each part consists of readings and videos containing background information on the steps of photosynthesis followed by the corresponding portion of a comic on photosynthesis. Students then use the background information in the module and the comic to identify their own misconceptions and questions and post these in an online discussion forum. The online module is followed by a live session in which the instructor uses the student discussion posts to clarify any remaining questions. Learning about photosynthesis in the unique visual format of a comic allows students to more easily visualize a process that they cannot see with their own eyes. Students enjoyed this activity because it makes learning photosynthesis fun and less intimidating. This lesson is powerful because it allows the instructor to hear from all students in the course via the discussion forum and then tailor the live discussion session to cover student identified problem topics.

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Learning Goals

Students will:

◊ understand the relationship between sunlight, carbon dioxide, and photosynthesis.

Plant Biology Learning Framework:

◊ How do matter and energy move through an ecosystem?

◊ How do structures of plants enable life functions?

Learning Objectives

Students will be able to:

◊ describe the overall purpose of photosynthesis.

◊ discuss the structure of a chloroplast and relate this to different parts of photosynthesis.

◊ summarize how the light-dependent reactions and the Calvin cycle transform light energy into chemical energy.

◊ explain how the light reactions are connected to the Calvin cycle.

INTRODUCTION

Photosynthesis is one of the most fundamental and important biochemical processes on the planet. It is the process by which plants convert light energy to chemical energy forming the basis of the earth's food chain, and producing oxygen. Because of its fundamental importance to biological science, photosynthesis is taught in most introductory biology courses. The topic of photosynthesis falls within *Vision and Change in Undergraduate Biology Education*'s core concept of "pathways and transformation of energy and matter"(1). Moreover, BioCore Guide, a nationally validated tool for interpreting *Vision and Change*, identifies the concept that "Energy captured by primary producers is stored as chemical energy. This stored energy can be converted through a series of biochemical reactions into ATP for immediate use in the cell" as a key competency for undergraduate biology students (2).

Photosynthesis is a complex process that many students struggle to understand. Students often memorize individual steps of photosynthesis and names of molecules instead of developing a conceptual understanding of how these processes work together. In addition, photosynthesis occurs at the molecular level, making it difficult for students to visualize. This lesson uses a long-form comic to help combat these difficulties by making the topic more fun and approachable.

The comic creates a story that helps students see the overall purpose of photosynthesis and provides alternative ways to visualize subcellular processes.

Comic books make science more approachable through visual and written narrative. Several studies report that most students prefer learning from narratives as opposed to traditional learning methods as they find narratives easier to comprehend, and feel that narratives improve their retention of materials (3–5). Other published lessons have used comics to help make science less intimidating by linking scientific content to a story (6–8). With comics in particular, students are not only exposed to a written story, but also have an accompanying visual representation. Coupling visual images with text has been shown to increase retention when compared to text that is not illustrated (9). In a non-majors biology course, using a comic to teach about evolution led to strengthened student attitudes towards biology and increased course scores in comparison to traditional teaching methods (8).

Comics provide a unique way to visualize a process that is "invisible" to students. Because photosynthesis happens at the molecular level, visualizations can help students to understand what is occurring. There are many challenges that come with visualizations of cellular processes, for example: molecules undergo conformational changes, and the scale at which something is occurring can be hard to conceptualize. Visualizations in a textbook on photosynthesis might range from an illustration showing the inputs and outputs for an entire plant, to a zoomed in image showing the reactions occurring at the level of the thylakoid membrane in the light-dependent reactions. Understandably, students struggle with understanding the size of cells and molecules in relationship to one another (10). Seeing multiple representations, both 2D and 3D, can help students gain a fuller understanding of molecular processes. Research suggests that 2D images that include dynamic cues can be as or more effective than animated images (11). Dynamic cues are found throughout comics as they help to tell the visual story, thus comics provide a great way for students to observe a molecular process in action. In this lesson, students interact with 3D images and animations by watching videos which they then compare to 2D images found in a comic. This helps them build the difficult skill of transitioning between different visual representations of cellular and subcellular processes.

In this lesson, students use the unique visualization of the comic to reflect on their past and current understanding of photosynthesis. Specifically, students identify ways in which the comic helped them recognize their own previous misconceptions. The students also assess whether the comic has helped them identify any additional parts of photosynthesis that they have struggled to understand. This approach gives students more control over their learning, and helps them practice the important metacognitive skill of recognizing when they do not fully understand material (12–15). Metacognitive activities like these have been shown to be effective to help students transfer what they have learned to new scenarios, a skill important for mastery of a topic and long-term retention (12, 13, 15). In this lesson students engage in metacognitive activities in an online classroom to help them build a deep conceptual understanding of photosynthesis.

Intended Audience

This lesson was developed for a majors-level introductory biology course at a large 4-year public research university, but is appropriate for any college level introductory biology course. It was designed for use in an online class, with both an online asynchronous component and an online synchronous component. The lesson could easily be adapted to be 100% online asynchronous or used in a hybrid online/in-person course. This approach is well suited for students that have a wide range of background knowledge, as students uncover their own misconceptions.

Required Learning Time

This lesson is divided into two main sections. The asynchronous portion takes about 90 minutes to complete, and the synchronous portion takes 20-30 minutes to complete (Table 1). The asynchronous module could easily be broken into two 45-minute sections, and the synchronous discussion could easily be extended to allow for more live discussion of student misconceptions.

Prerequisite Student Knowledge

Students are expected to have already learned about the basics of bioenergetics. Specifically, they should understand the basics of anabolic and catabolic reactions and should be able to explain the role those chemical reactions play in the transfer of energy. This information is provided in almost all introductory biology textbooks. Instructors could use the freely available Chapter 6 "Metabolism" in OpenStax Biology 2e (16).

Prerequisite Teacher Knowledge

The instructor should understand the processes of photosynthesis at the level of a major's level introductory biology textbook, for example Chapter 8 "Photosynthesis" in OpenStax Biology 2e (16). This coverage includes details of the structures used in photosynthesis as well as what happens during the light-dependent reactions and the Calvin cycle. The materials provided in the online module itself can also be used by the instructors to prepare for the lesson. In addition, instructors should be comfortable using their learning management system. Specifically, they will need to be able to create a module and a discussion forum within their learning management system. They also will need to be able to schedule and host a live online meeting through Zoom or a similar software. In addition, instructors should be knowledgeable the Universal Design for Learning (UDL) guidelines (17).

SCIENTIFIC TEACHING THEMES

Active Learning

This lesson engages students through a variety of active learning techniques. First, students take an active role in learning the content by completing guided notes as they work their way through the module. Second, they interact with one another in an online discussion board, in which they identify parts of the comic that either helped their understanding of a topic or led to additional questions on the topic. Since students are required to respond to each other's posts, they generate a unique interactive discussion on their own misconceptions or questions about photosynthesis. Finally, the instructor is then

able to read through the posts to tailor the synchronous wrap-up session at the end of the lesson covering specific student identified topics.

Assessment

Student discussion posts were graded based on effort. Specifically, students who followed the instructions provided for the discussion post received full credit for the assignment. In addition, student's notes guides were also graded based on effort. Using the discussion posts and notes guides for formative assessment allows students to receive feedback from their peers and their instructor. In addition, it allows the instructor to modify the topics discussed during the synchronous wrap-up session to fit the students' needs and misunderstandings. Finally, the lesson is evaluated through exam questions that test the learning objectives of the module.

Inclusive Teaching

This lesson incorporates several of the Universal Design for Learning (UDL) guidelines (17). All students contribute and share their thoughts and ideas in the online discussion board. This helps to engage students by minimizing threats and distractions (UDL 7.3), which allows quieter students to be heard. The asynchronous portion of this lesson is self-paced, and in several parts, allowing flexibility in when and after how much time students complete the assignment. The guided notes that students fill out as they work through the module provides options to help students with comprehension by helping to maximize transfer and generalization (UDL 3.4). This lesson provides multiple means of engagement by allowing individual choice (UDL 7.1) of topics that students post about, and posts that they respond to. This approach allows the instructor to craft the synchronous portion of the lesson to cover topics on which students need the most help. In addition, the comic helps to make the complex topic of photosynthesis less intimidating to students, thus increasing interest.

LESSON PLAN

This online module was designed to be used in one asynchronous, and one synchronous online class session. In the asynchronous portion, students watch and read a series of videos and readings, and compare the information in these to a comic about photosynthesis. Students share misconceptions or questions they have about photosynthesis related to the comic with their classmates through an online discussion forum. This session is estimated to take about 90 minutes, although it could easily be divided into two 45-minute sessions, in which students tackle the light-dependent reactions of photosynthesis in the first session, and the light-independent reactions in the second session. The asynchronous component is followed up by a synchronous wrap-up discussion during the next class. The wrap-up discussion is created by the instructor to address the misconceptions and questions that students have submitted to the online discussion forum (Table 1).

Overview of online module format

The asynchronous portion of the lesson was set up as a module within the learning management system Canvas (S1. Photosynthesis Through Comics - Student Module Pages). Part 1-4 of the module were each set up as separate pages in Canvas and each arranged as follows:

- Outline of learning objectives
- Text introducing the material and a reminder to fill out the provided notes guide (S2. Photosynthesis Through Comics - Notes Guide)
- Content videos
- Text describing the purpose of not only watching the content videos but reading and comparing them to a comic about photosynthesis
- Link to the discussion prompt to be completed at the end of the module
- Link to the portion of the comic that corresponds to the content covered in this part of the module

Exact wording for each page of the module can be found in the Supporting Materials (S1. Photosynthesis Through Comics - Student Module Pages). The module was set up so that once the student finishes one part of the module they automatically move to the next part. Students were able to move through the online lesson without any additional help from the instructor.

Breakdown of content for each part of the online asynchronous module

In Part 1 of the online module students are introduced to the general purpose of photosynthesis. Through a canvas page, they read a little bit about photosynthesis and watch two short videos that focus on the reactants and products of photosynthesis as well as the big picture of what is occurring during photosynthesis (Part 1 of S1. Photosynthesis Through Comics - Online Module Pages). As they work through this material they fill out a corresponding notes guide (Part 1 of S2. Photosynthesis Through Comics - Notes Guide). They are then introduced to the discussion forum assignment (S3. Photosynthesis Through Comics - Discussion Prompt). Specifically, they are told that they are going to read through a photosynthesis comic a few pages at a time, and that by the time they have completed the entire comic they will need to also have completed a discussion post in which they pose a question about photosynthesis or give an example of how the comic helped them clear up a misconception they had about photosynthesis. Finally, they are prompted to read Part 1 of the comic (S4. Photosynthesis Through Comics - Comic Part 1). After finishing Part 1, they click an arrow within the learning management system to progress to Part 2.

In Part 2 of the online module the students read and watch videos to learn more about the light-dependent reactions and the Calvin cycle (Part 2 of S1. Photosynthesis Through Comics - Online Module Pages). This part of the lesson has the students determine for each part of photosynthesis: where it occurs, the inputs and outputs, and its overall purpose. Students then learn how the light-dependent reactions and the Calvin cycle are connected. As in Part 1, students follow along filling out the next section of their notes guide (Part 2 of S2. Photosynthesis Through Comics - Notes Guide). When finished, they are prompted to read through the next few pages of the comic that discuss the content covered in Part 2 (S5. Photosynthesis Through Comics - Comic Part 2). After finishing Part 2, they click an arrow within the learning management system to progress to Part 3.

Part 3 of the online module goes in depth on what happens in the light-dependent reactions of photosynthesis. Through short readings and videos students learn about the pigments involved in photosynthesis as well as the reactions that make up the light-dependent reactions (Part 3 of S1. Photosynthesis Through Comics - Online Module Pages). They fill out the next section of their notes guide (Part 3 of S2. Photosynthesis Through Comics - Notes Guide), and are then asked to read through the next part of the comic (S6. Photosynthesis Through Comics - Comic Part 3). After finishing Part 3, they click an arrow within the learning management system to automatically progress to Part 4.

Part 4 of the online module focuses on what happens in each phase of the Calvin cycle and the overall reactants and products of the Calvin Cycle (Part 4 of S1. Photosynthesis Through Comics - Online Module Pages). Students fill out the final section of the notes guide as they work through the material (Part 4 of S2. Photosynthesis Through Comics - Notes Guide). They are then asked to read the final pages of the comic that focus on the Calvin Cycle (S7. Photosynthesis Through Comics - Comic Part 4). After finishing Part 4, they click an arrow within the learning management system to progress to the discussion forum.

Once students have worked through Parts 1-4 and read the full comic, they are prompted to complete the online discussion post based on what they have learned. Here, through an online discussion forum, students are required to either post a question that was inspired by the comic or post a page of the comic that helped with their understanding of a complicated aspect of photosynthesis. After posting, they are required to comment on another student's post either providing a follow up question, answering a student's question, or providing additional information about how a particular page of the comic mentioned in another student's post also helped them. The instructor monitors the discussion board and responds to any questions that were not already answered by students in the course. Full post requirements and comment prompts are found in S3. Photosynthesis Through Comics - Discussion Prompt. The full comic with numbered pages is S8. Photosynthesis Through Comics - Comic All Pages.

Synchronous Wrap-up Session

By reviewing the discussion posts, the instructor is able to identify common student problems. During the following synchronous online class, the instructor can share several of the student posts, along with images of the comic. These posts and images are then used as starting points to discuss and clarify any areas of confusion (S9. Photosynthesis Through Comics - Example in-class discussion). This is done through a live Zoom session. If the course is fully asynchronous this could also be done in a recorded video by the instructor.

TEACHING DISCUSSION

This lesson is intended to teach students about photosynthesis. The most important aspect of the lesson is the reflection and online discussion that students have regarding the photosynthesis comic. The purpose of the online discussion forum, and the synchronous online session that follows, is to allow students to identify misconceptions or points of confusion that they previously had, or still have regarding photosynthesis. Students identify their misconceptions through their own discussion post and when responding to other student posts. For example, one student expressed in their discussion post that the comic helped them realize the important role that water plays in photosynthesis. They mentioned that in the comic they could actually see how electrons leave photosystem II and need to be replaced by those in the water. In a response post to this, another student commented that this also helped them, because they had also been confused about why water and its electrons are so important in photosynthesis. This discussion gave students the chance to reflect on their own learning, an important metacognitive strategy (12, 13, 15), and also to see that other students had similar points of confusion.

Almost all of the students indicated in their discussion post that the comic helped them understand photosynthesis by providing simple visuals. One student specifically mentioned that they redrew several of the images to help their understanding, and another commented on how the comic helped them understand where the different processes of photosynthesis were actually located. Other students indicated that the comic's story helped them develop their understanding of how the individual steps linked together. These student comments provide additional evidence that the unique characteristics of visual and written content in a comic can help students develop a better understanding of a complex topic.

This lesson gives every student, even in a large course (70 in this case), a chance to discuss and get answers to their questions. The students also get the opportunity to answer each other's questions, and the instructor can use the information provided in the discussion forum to structure the next synchronous session to address still unanswered questions. The biggest strength of this lesson is the opportunity for every student to share their ideas, and for the instructor to be able to easily identify subtopics with which the students struggle.

The comic generated a very robust discussion and, based on student posts, seemed to really help students better understand photosynthesis. For example, one topic that students have struggled with in this course in the past is understanding the role that hydrogen ions play in photosynthesis. There is a wonderful illustration showing cytochrome C putting more and more hydrogen ions into the thylakoid lumen. The next panel in the comic shows the lumen full of hydrogen ions and explains how that concentration gradient helps to make ATP (Figure 1). The images allow students to easily visualize the accumulation of these ions creating a concentration gradient. Many students posted that images from the comic helped them understand how hydrogen ions related to photosynthesis.

This lesson was taught in an online course with ~70 students. The format of the course, and the lesson as written, is half online asynchronous, and half online synchronous. This lesson could easily be modified for a fully online asynchronous course by conducting the wrap-up session as an asynchronous recording made by the instructor. Alternatively, this lesson could easily be modified for a fully in-person course. For example, the online module could still be used as homework, and the synchronous session could be done in a live class. Another option would be to provide the major photosynthesis content

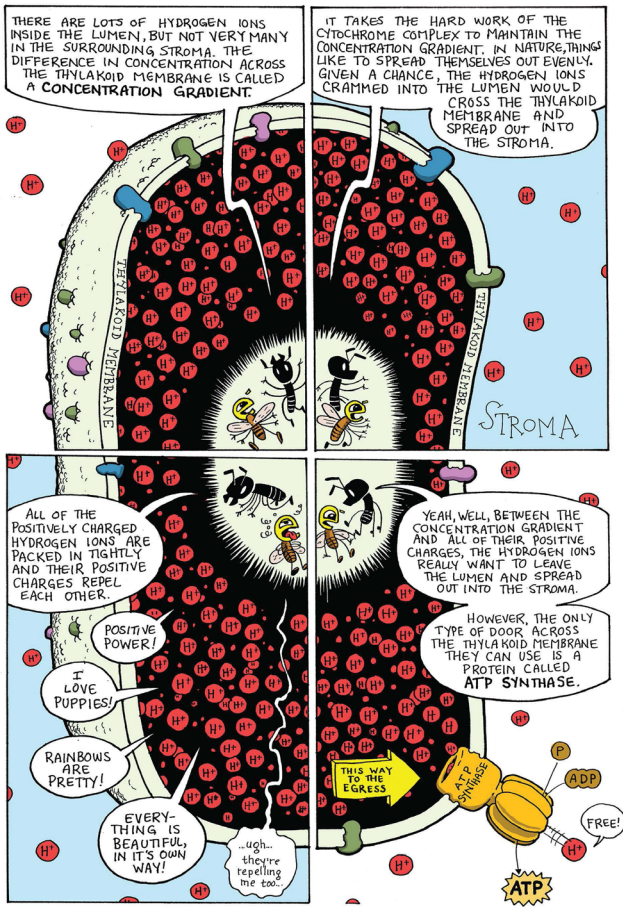

Figure 1. A panel from Jay Hosler's comic Photosynthesis or "gimme some sugar" (© 2020 Jay Hosler, used with permission from the author) that shows the importance of the hydrogen ion concentration gradient in the process of photosynthesis. This image was commonly cited by my students as helpful in their understanding of the role of hydrogen ions in photosynthesis.

in class rather than through online videos. As homework, students could complete the online discussion board based on the photosynthesis comic. This would be a great way for students to reflect on the topics they have learned in class and identify their own misconceptions. The following live class period could then be used for the wrap-up discussion.

Although photosynthesis is the focus of this lesson, the technique of using a comic in a discussion forum as described here can easily be used for other topics in biology. In this course, the students completed a nearly identical activity on the topic of cellular respiration. The cellular respiration comic along with many other freely available biology comics can be found on Jay Hosler's website.

Overall, this approach is an effective way to help students and instructors identify and clarify common student misconceptions. The use of a comic makes the complexities of photosynthesis less intimidating and allows students to visualize biological processes happening at the molecular level. The discussion forum encourages participation from all students, and helps the students feel comfortable asking questions and figuring out what they still do not fully understand.

SUPPORTING MATERIALS

- S1. Photosynthesis Through Comics - Online Module Pages
- S2. Photosynthesis Through Comics - Notes Guide
- S3. Photosynthesis Through Comics - Discussion Prompt
- S4. Photosynthesis Through Comics - Comic Part 1
- S5. Photosynthesis Through Comics - Comic Part 2
- S6. Photosynthesis Through Comics - Comic Part 3
- S7. Photosynthesis Through Comics - Comic Part 4
- S8. Photosynthesis Through Comics - Comic All Pages
- S9. Photosynthesis Through Comics - Example in-class discussion

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Table 1. Complexities of photosynthesis teaching timeline

Activity	Description	Estimated Time	Notes
Online Asynchronous Session			
Part 1: Photosynthesis is a redox reaction	General introduction to the overall purpose of photosynthesis.	15 minutes	Module page including introduction, two video resources, links to Part 1 the comic strip and an introduction to the comic strip discussion assignment (Part 1 of S1. Photosynthesis Through Comics - Online Module Pages).
Part 2: Structures involved in photosynthesis (What happens where?)	Exploration of the leaf structure and how the light reactions are interconnected with the Calvin cycle.	15 minutes	Module page with introduction, two video resources, and Part 2 of the comic strip (Part 2 of S1. Photosynthesis Through Comics - Online Module Pages).
Part 3: Light-dependent reactions	A deeper discussion of how light energy is converted into chemical energy. Includes a discussion of the electron transport chain.	30 minutes	Module page with introduction, two video resources, and Part 3 of the comic strip (Part 3 of S1. Photosynthesis Through Comics - Online Module Pages).
Part 4: Calvin Cycle	Exploration of the major processes that occur in the Calvin Cycle.	20 minutes	Module page with introduction, three video resources, and Part 4 of the comic strip (Part 4 of S1. Photosynthesis Through Comics - Online Module Pages).
Discussion board post and response	Students post into an online discussion forum, and respond to another student's post.	10 minutes	Full prompt including post and response requirements (S3. Photosynthesis Through Comics - Discussion Prompt).
Online Synchronous Wrap-up Session			
Wrap-up discussion	Live online session highlighting and discussing common areas of confusion and unanswered discussion questions.	20 minutes	Slides include the text posted by the students in the discussion board as well as the image from the comic they referenced (S9. Photosynthesis Through Comics - Example in-class discussion).