How do biology undergraduates "explain" photosynthesis? Investigating student responses to different constructed response question stems

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Abstract

One goal of assessment is to provide instructors with formative feedback about their students' understanding or difficulties with class material. When compared to selected- response (e.g. multiple choice) items, constructed response (open, written answer) questions can give a richer picture of what students know, as long as the question stem is written carefully to elicit student thinking. In previous work with a constructed response question on how plants gain biomass, we found that many students did not respond to the question by explicitly naming a process. This study investigated how responses change when the question stem is altered to explicitly ask for the process by which biomass is added to plants. The two versions of the stem were administered to 1237 students across three semesters. We analyzed the responses using IBM SPSS Text Analytics for Surveys software to extract relevant terms and categorize them. The process category *photosynthesis* showed a significant increase in frequency from the first version of the stem to the second. The responses to stem version two that named photosynthesis as their only process were less likely to use carbon dioxide and glucose than the responses to stem version one that named photosynthesis as the only process. Our results suggest novices (students) and experts (faculty) have different understandings of what constitutes an "explanation" in a scientific context and that constructed response questions must be worded carefully so that students interpret the questions correctly.

Introduction

One of the key purposes of assessment is to provide instructor-formative feedback about students’ comprehension of course material (NRC 2001) and provide a detailed look into students’ reasoning skills and understanding of key concepts that can directly influence classroom instruction (Seymour 2002, AAAS 2009). Research on item types has shown that constructed response questions can reveal a wide range of student ideas as well as misconceptions that may otherwise be hidden using multiple choice-type tests (Lyons et al. 2011, Birenbaum & Tatsouka 1987, Kuechler & Simkin 2010). However, one challenge of using constructed-response questions is writing the question stem so that it is clear to the students the amount of scientific detail they should provide in their answers.

Students may interpret a constructed-response question differently than experts, and the information that should be included in their answer is not always obvious to them. An expert understands that scientific reasoning requires being able to follow the steps of a system and identify processes within the system (Ben-Zvi Assaraf, & Orion 2005), and that those processes are constrained by over-arching scientific principles, such as conservation of mass (Anderson 2009). A novice may not see the need to reason with over-arching principles and specific processes so the wording of the question stem is particularly important.

Often it is unclear whether students use informal reasoning because they do not understand the targeted concepts or because they do not see that answering the question requires scientific principles. The following are examples of student responses from a question that asked where plant biomass comes from. Each of them shows some incorrect ideas without naming the process that they are describing.

> *This huge increase in biomass can be attributed to the ATP available in the tree to do the chemical, mechanical and transport work necessary for it to grow. When the tree was a seedling, it took CO2 gas, sunlight and water so that the chloroplasts can make ATP which powers the cells to deliver the proper nutrients to the roots and stems so that they grow. The process releases oxygen. The ATP is synthesized in the thylakoids of the chloroplasts when NADPH is oxidized. ATP allows the cells to carry out mitosis and divide, hence the tree grows, the ATP is then oxidized back to ADP or NADPH and the cycle starts all over again. The biomass is made of polymers of carbons and oxygens and hydrogens and would be released as CO2.*

> *The increase is due to a large absorption of minerals and organic materials through the soil then joining their benefits with H2O, O2 and sunlight to help reach maximum production.*

When students do not name a process in their answer, it is difficult to determine if they have problems with tracing matter or if they understand photosynthesis correctly but did not think the question requires such information. To better understand the impact of question wording, we investigated the impact on students’ written explanations when they were explicitly asked to identify a process in their response.

Methods

In the fall semester of 2009 one of two possible forms of a constructed response question was given to each student on a midterm exam in an introductory Cells and Molecules biology course at Michigan State University. The two forms of the stem were identical except for the organism named, which was corn in one stem and a maple tree in the other. The different surface features of the two forms of the test did not impact student responses (Lyons et al. 2011). The prompt asks students to "explain" the huge increase in biomass of the organism. While an expert would interpret "explain" to entail a process, only 71% of student responses named a process. In falls of 2010 and 2011, the stems were revised to additionally ask students to name the process that adds biomass to the plant (See Figure 1).

Stem Version One (Fall 2009):
A mature maple tree can have a mass of 1 ton or more (dry biomass, after removing the water), yet it starts from a seed that weighs less than 1 gram. Explain this huge increase in biomass.

Stem Version Two (Fall 2010 and Fall 2011):
A mature maple tree can have a mass of 1 ton or more (dry biomass, after removing the water), yet it starts from a seed that weighs less than 1 gram. Explain where this biomass comes from and by what process.

Figure 1: Version one and version two of the question stem.

In the fall semester of 2009, 385 students were given version one of the constructed response question on the exam. In the fall of 2010 and fall 2011, 394 students and 458 students, respectively, were given version two of the stem on their exam. The three semesters were similar demographically (Table 1). Students from all three semesters were given the question on midterm exams that were post-instruction on photosynthesis. The questions were worth the same amount of points on each exam and students recorded their answers in their test booklets. Their responses were transcribed into a spreadsheet for further analysis.

Table 1
Demographic Information for Fall 2009, Fall 2010, and Fall 2011 Semesters

Demographic	Fall 2009[a]	Fall 2010[b]	Fall 2011[c]
Ethnicity			
White	80.3%	80.7%	80.2%
African American	6.1%	8.4%	4.7%
Asian	4.1%	4.2%	5.4%
Hispanic	3.3%	2.5%	4.7%
Other	2.0%	1.7%	3.0%
Not Reported	4.1%	2.7%	1.9%
Gender			
Male	38%	40%	61%
Female	62%	60%	39%
Year			
Freshman	4.3%	3.0%	11.4%
Sophomore	53.5%	53.8%	61.2%
Junior	29%	33.3%	17.9%
Senior	13.3%	9.9%	9.5%

[a]n=391. Mean cumulative GPA=2.977. Mean course grade=2.20. [b]n=405. Mean cumulative GPA=2.997. Mean course grade=2.28. [c]n=464. Mean cumulative GPA=3.012. Mean course grade=2.22.

Analysis

We analyzed the data using IBM SPSS Text Analytics for Surveys V4.0 (STAS). STAS is lexical analysis software that can recognize words and phrases from written data, which is called extracting *terms*. These terms are then typically aggregates in *categories* specified by the user that contain responses with a similar trait or traits, with an attempt to make the categories fairly fine-grained conceptual assemblages. For example, the category "*glucose*" includes responses that mention glucose, sugar, cellulose, starch, and G3P or any of their synonyms and misspellings. The text analysis was done with libraries we previously developed, and contain lists of terms to be extracted relevant to cell metabolism and photosynthesis (Lyons et al. 2011, Moscarella et al. 2008). Since previously made libraries were used, only new categories had to be developed based on relevancy to this project.

Our lexical analysis included sixteen categories to classify the responses. Each response can be put into multiple categories depending on the content of the answer. For example, the following student response to stem version one was put into three categories: *substance*, *energy*, and *glucose*.

> *As the tree grows it makes organic materials such as glucose. As these organic molecules build up some are used to make energy while others are stored up, causing the tree to grow. The tree forms more and more cells which increases the weight of the tree.*

While students may have different ideas of what makes something a process, according to Wilson et al. processes are "…open systems that exchange matter and energy across defined boundaries" (2006). *Photosynthesis*, *cellular respiration*, *cell division*, *electron transport chain*, and *solar radiation* are lexical categories, which we considered processes under this definition. The categories *carbon, carbon dioxide,* and *glucose* represent sources and products of photosynthesis, or inputs and outputs. To determine if the changed question wording produced different student responses, we performed an independent two-sample T-test on each category and used a Bonferroni correction to adjust the significance level to .003, since sixteen tests were done in total.

Results

The distributions of student responses for both versions of the stem are shown in Figure 2. Independent two-sample T-tests showed a significant ($p<.003$ after Bonferonni correction) increase in the process categories *photosynthesis* (Version 1 $\bar{x}$=.62; Version 2 $\bar{x}$=.72), *electron transport chain* (Version 1 $\bar{x}$=.14; Version 2 $\bar{x}$=.07), and *solar radiation* (Version 1 $\bar{x}$=.36; Version 2 $\bar{x}$=.45). The input and output categories *carbon* (Version 1 $\bar{x}$=.14; Version 2 $\bar{x}$=.09), *carbon dioxide* (Version 1 $\bar{x}$=.58; Version 2 $\bar{x}$=.43), and *glucose* (Version 1 $\bar{x}$=.50; Version 2 $\bar{x}$=.40) showed a significant decrease in frequency ($p<.003$). The categories *cellular respiration* (Version 1 $\bar{x}$=.18; Version 2 $\bar{x}$=.24; $p<.010$) and *cell division* (Version 1 $\bar{x}$=.12; FS10 $\bar{x}$=.17; $p<.031$) were two process categories that did not show a significant difference in the number of responses that used them.

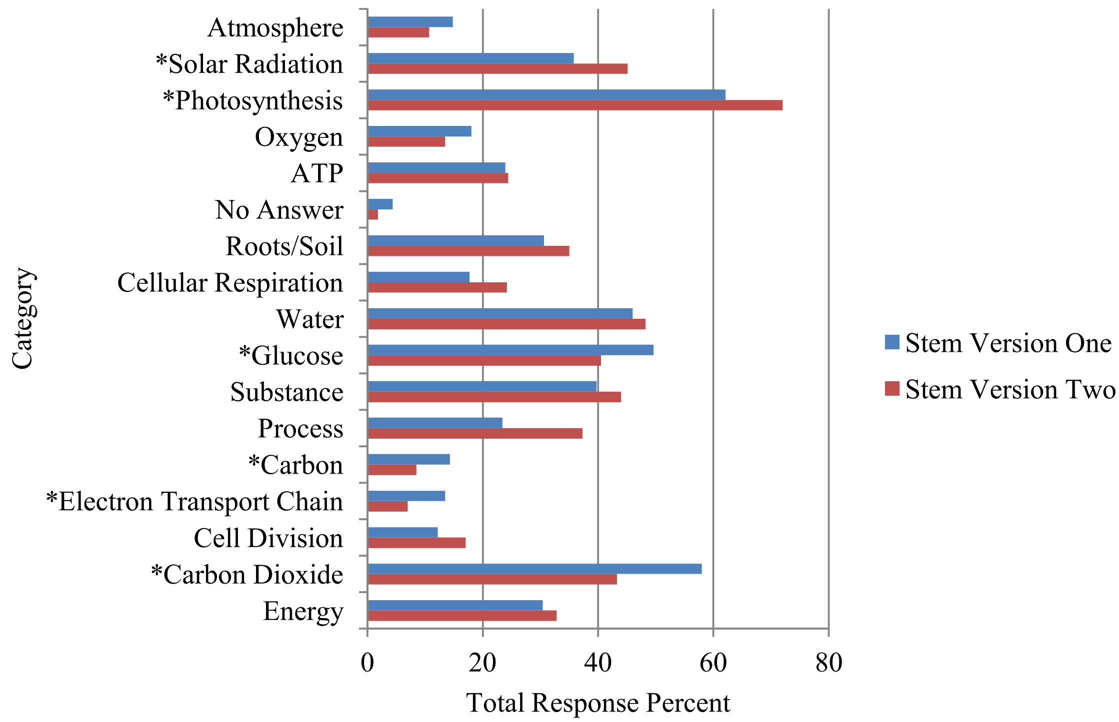

Figure 2: Distribution of student responses to stem version one and stem version two.
* Denotes categories that showed a significant change (independent two-sample T-test, $p<.003$) from stem version one to stem version two.

As a negative control, we examined three categories *substance* (Version 1 $\bar{x}$=.40; Version 2 $\bar{x}$=.44; $p<.158$), *water* (Version 1 $\bar{x}$=.46; Version 2 $\bar{x}$=.48; $p<.475$), and *ATP* (Version 1 $\bar{x}$=.24; FS10 $\bar{x}$=.24; $p<.837$). Since these categories do not represent processes, we did not expect them to show a significant change in frequency between semesters. As expected, the change was insignificant for all three.

The category called *process* contained only a single term "process" and was used to see if there was a change in how frequently student use a word once it is added to the question stem. The increase in students' use of this category from the first version of the stem to the second was significant (FS09 $\bar{x}$=.23; FS10 $\bar{x}$=.35; $p< .000$).

Table 2 shows the relationship between the biomass inputs and outputs that showed significant decrease across stem versions. The table shows three different groups of responses: those that contained photosynthesis as the only process, those that named cellular respiration as the only process, and those that named both photosynthesis and cellular respiration.

Figure 4 shows examples of responses to stem version one, in which students were only asked to explain and do not explicitly state which process or processes they believe add biomass to plants. In contrast Figure 5 shows responses to stem version two, in which students were directed to explain with a mass source and a process, and that name the process they are discussing.

Table 2

Students' Use of Biomass Inputs and Outputs in Stem Version One and Stem Version Two

	Version One		Version Two	
	Mean	SD	Mean	SD
Photosynthesis Only[a]				
Carbon	.14	.35	.10	.30
Glucose	.63	.48	.44*	.49
Carbon dioxide	.65	.47	.46*	.49
Respiration Only[b]				
Carbon	.21	.40	.09*	.29
Glucose	.63	.48	.55	.49
Carbon dioxide	.63	.48	.53	.50
Photosynthesis and Respiration[c]				
Carbon	.19	.39	.1	.30
Glucose	.66	.47	.59	.49
Carbon dioxide	.95	.49	.94	.50

*Note.*The rows represent responses that contained photosynthesis as the only process, respiration as the only process, and photosynthesis and respiration both as processes that add biomass to plants.

[a]n=622. [b]n=273. [c]n=227

*Means different between version one and version two ($p < .05$ by paired t-test).

This large increase in biomass is from the absorption of light energy converted into chemical energy the seeds can use to grow. Also, the absorption of materials from the environment the seeds can use to make ATP and grow.

This huge increase in mass is primarily due to the absorption of various organic molecules from the soil and products from various cellular metabolic processes. Through the absorption of organic molecular and nutrients via the roots the maple tree is able to grow and develop while harvesting the nutrients within and continuing to develop on the other hand, an increase in mass can also be accounted for through the cellular metabolic processes which intake other molecules, converting them to ATP and other substances to use inside the cell. But overall, without the exception of water, the mass increase is most reliant upon the uptake of nutrients from the soil.

The maple tree absorbed lots of H2O over the years and used that to make ATP and glucose. Both of these products were used to grow this tree and some glucose may have been stored away. So even though the H2O was removed, it still is able to keep its size due to its large storage amounts of nutrients, glucose and water.

The plant used CO2 from the air and sunlight to produce sugar, which is used to build structures within the plant. This process is repeated over many years.

Figure 4: Responses to stem version one that do not name a process.

Process responsible for increased biomass is photosynthesis. The biomass came from the incorporation of CO2 gas from the atmosphere that was delivered to molecules in the green leaves, sunlight helps create glucose and nutrients moved to roots.

This increase in biomass comes from the CO2 the plants in took during photosynthesis. With the CO2 it in took it fixed the carbon, making glucose as a byproduct, further increasing its net energy, allowing the plant to grow more.

This biomass came from the processes of photosynthesis and the calvin cycle that occur within the leaves of these plants. In photosynthesis the plant takes in sunlight and uses this energy to produce ATP and NADPH for the calvin cycle. Then, in the calvin cycle the plant uses the ATP and NADPH, and combines it with CO2 from the air to produce sugar or starch. This starch accumulates in the plant leaving the plant weighing more than it was initially.

Biomass was gained from absorbing H2O and sunlight, and giving off CO2. This process is cellular respiration.

Biomass comes from the process of photosynthesis. The seed begins to utilize the H2O and the organic nutrients that surround it in the soil. As the tree begins to grow, cellular respiration occurs from water and light absorption, giving off excess CO2. Chloroplasts produce ATP, giving the plant cells energy to replicate. Most of the biomass is from most of the nutrients surrounding the tree and the resulting production of photosynthesis.

Figure 5: Responses to stem version 2 and that specifically name a process.

Discussion

Responses that name a process provide a richer look into student ideas than responses that do not name the process they are describing. For our photosynthesis question, naming a process helps the instructor verify what the students believe is involved in adding biomass to plants. Naming a process helps clarify whether a student with misconceptions misunderstood the inputs and outputs of photosynthesis or was confused about which process adds biomass.

Photosynthesis and *solar radiation* were two lexical categories that reference a process and showed a significant increase in responses from version one to version two of the stem. When students respond to the first version (Figure 4), it is possible that they may actually know that photosynthesis and solar radiation were processes involved in adding biomass to plants, but did not consider that the call to “explain” needed a process to be considered complete. This can be seen in responses in Figure 4 where students explained the process they thought adds biomass to plants but did not name it. Figure 5 shows responses from version two with similar ideas but that specifically name the processes they are describing. Since only the categories *photosynthesis* and *solar radiation* changed, the stem version two was more successful than stem version one at verifying correct student responses, and no better at identifying misconceptions.

Although the reworded stem improved inclusion of a process, the responses showed an overall decreased inclusion of appropriate inputs and outputs. Responses to stem version two that mentioned photosynthesis as the only process were less likely to use the categories *carbon dioxide* and *glucose* than responses to stem version one that mentioned photosynthesis as the only process (Table 2). For responses to stem version two that correctly named photosynthesis, being more explicit about naming the process may have come at the cost of specifying the source of biomass and its final form on the plant. There was not a significant change in the number of responses that had the categories *cellular respiration* and *cell division,* which represent processes for our stem. However, the responses to stem version two that named cellular respiration as the only process were less likely to contain the category *carbon,* indicating less of an emphasis on the movement of carbon from input to output in cellular respiration. For responses that had heterogeneous ideas by using both photosynthesis and cellular respiration, there was no change in the use of *carbon, carbon dioxide,* or *glucose* from stem version one to stem version two.

Alignment with Interview Data

A similar photosynthesis question, shown below, was used by Parker et al. (2012) in interviews with students to further probe their thoughts post-photosynthesis instruction.

> Each spring, farmers plant about 5-10 kg of seed corn per acre for commercial corn production. By the fall, this same acre of corn will yield approximately 4-5 metric tons of harvested corn. Which of the following processes contributes the most to this huge increase in biomass?

In the interviews, students often explained their answer as being either scientific or "logical." One student admitted that she did not know how to answer the question scientifically. When she was asked to answer it with common sense she said that biomass comes from nutrients in the soil and light from the sun. Another student's answer was correct in the interview but different than what she selected on the multiple choice exam. She said that on the exam she was "using common sense", and so she did not think of photosynthesis. The examples from our study in Figure 4 show instances of informal reasoning similar to what was obtained through interviews.

After we changed the stem to ask students to name the process that adds biomass to plants we saw an increase in the percentage of responses that named photosynthesis. This larger group of students using photosynthesis may include those who knew the process but would not name it in their response unless they were prompted to do so. Since students differ from experts on what they think constitutes a complete answer, it is important that the question stem be designed to elicit the desired information.

Conclusion

Scientific explanations of phenomena such as mass gain in plants require a mechanism or process. In our research we discovered that if the question did not ask students to name a process, fewer students interpreted the directive to "explain" to require naming a process in their response. The results of this study revealed that changing the stem of a constructed-response question to explicitly ask students to name the process by which biomass is added to plants resulted in a significantly higher percentage of students naming photosynthesis and solar radiation in their answers.

Altering the stem to ask for a process changed the way that students answered in another way as well. The students who used photosynthesis as the only process in their response identified the inputs and outputs of photosynthesis less frequently than did students that recieved the first version of the stem. Similarly students that named cellular respiration as their only process were less likely to use carbon in their answer to stem version two than stem version one. No change was seen in responses that used both photosynthesis and cellular respiration together. It is possible that with an added request to name a process in the stem the students' focus moved away from identifying the source of biomass and its final form in the plant. On the other hand, it is also possible that some students are engaged in procedural display (Bloome et al. 1989) and, when prompted for a "process" simply named the first process that came to mind (plants <> photosynthesis.)

The implication of this study on constructed response question writing is that even small changes in wording can influence how students respond, which is consistent with other literature on novice's fragile knowledge in complex domains (Alexander 2003, Hmelo-Silver et al. 2007). The question should elicit responses that portray student understanding as accurately as possible, but this can be challenging. Students approach questions differently than experts and they often use prior experiences, informal reasoning, or procedural display when answering. If the question is written so that it is clear to novices the amount of scientific detail they should provide in their answer, then they will provide more meaningful responses.

References

Alexander, P. A. (2003). The development of expertise: The journey from acclimation to proficiency. *Educational Researcher, 32(8), 10-14.*

American Association for the Advancement of Science (2009). Vision and change in undergraduate biology education: A call to action. *Conference Proceedings, AAAS 2009 National Conference.*

Anderson, C.W. (2009). *Learning progressions for principled accounts for processes in socio-ecological systems*. Paper presented at the NARST 2009 Annual International Conference, Garden Grove, CA.

Ben-Zvi Assaraf, O., & Orion, N. (2005). Development of system thinking skills in the context of earth system education. *Journal of Research in Science Teaching, 42: 518 –560.*

Birenbaum, M., & Tatsouka, K. K. (1987). Open-ended versus multiple-choice response formats - It does make a difference for diagnostic purposes. *Applied Psychological Measurement, 11: 329-341.*

Bloome, D., Puro, P., & Theodorou, E. (1989). Procedural display and classroom lessons. *Curriculum Inquiry, 19(3), 265-291.*

Hartley, L.M., Wilke, B.J., Schramm, J.W., D'Avanzo, C., & Anderson, C.W. (2011). College student's understanding of the carbon cycle: Contrasting principle-based and informal reasoning. *BioScience 61: 65–75.*

Hmelo-Silver, C. E., Marathe, S., & Liu, L. (2007). Fish swim, rocks sit, and lungs breathe: Expert-novice understanding of complex systems. *Journal of the Learning Sciences, 16(3), 307 - 331.*

Kuechler, W.L., & Simkin, M.G. (2010). Why is performance on multiple-choice tests and constructed-response tests not more closely related? Theory and an empirical test. *Decision Sciences Journal of Innovative Education 8: 55–73.*

Lyons, C., Jones, S., Merrill, J., Urban-Lurain, M., & Haudek, K.C. (2011) *Moving across scales: Using lexical analysis to reveal student reasoning about photosynthesis.* Paper presented at the NARST 2011 Annual International Conference, Orlando, FL.

Moscarella, R.A., Urban-Lurain, M., Merritt, B., Long, T., Richmond, G., Merrill, J.,…Wilson, C. (2008). *Understanding undergraduate students' conceptions in science: Using lexical analysis software to analyze students' constructed responses in biology.* Paper presented at the NARST 2008 Annual International Conference, Baltimore, MD.

National Research Council. (2001). *Knowing what students know: The Science and Design of educational assessment*. Washington, DC: National Academy Press.

Nehm, R.H., Ha M., & Mayfield, E. (In Press). Transforming biology assessment with machine learning: Automated scoring of written evolutionary explanations. *Journal of Science Educational Technology.*

Parker, J.M., Anderson, C.W., Heidemann, M., Merrill, J., Merritt, B., Richmond, G., & Urban-Lurain, M. (*In Press*). Exploring undergraduates' understanding of photosynthesis using Diagnostic Question Clusters. *CBE Life Sciences Education.*

Seymour, E. (2002). Tracking the processes of change in US undergraduate education in science, mathematics, engineering, and technology. *Science Education 86(1): 79-105.*

Urban-Lurain, M., Moscarella, R., Haudek, K.C., Giese, E., Merrill, J.E., & Sibley, D.F. (2010).

Insight into student thinking in STEM: Lessons learned from lexical analysis of student writing. *National Association for Research in Science Teaching, 83.*
Wilson, C.D., Anderson, C.W., Heidemann, M., Merrill, J.E., Merritt, B.W., Richmond, G.,… Parker, J.M. (2006). Assessing students’ ability to trace matter in dynamic systems in cell biology. *CBE Life Sciences Education 5(4): 323-33.*