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Storytelling as a Tool to Enhance Conceptual Knowledge in Cell Biology

Kirill Kiselyov[a] and Christian D. Schunn[b]
[a]Department of Biological Sciences, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
[b]Learning Research and Development Center, University of Pittsburgh, Pittsburgh, Pennsylvania, USA

Research in a range of disciplines shows that many undergraduate students struggle with aggregating complex knowledge components into a complete picture and incorporating research literature into the learning process. To build and improve on the practice of project-based approaches to teaching cell biology, we transformed an undergraduate cell biology class by introducing the concept of storylines that are selected by groups of students for development throughout the semester. Each storyline integrates molecular and organellar concepts discussed during the semester into the cell- and tissue-level functions, conditions, or diseases shared and discussed during online poster sessions. Three semester-long studies conducted with an undergraduate cell biology class utilized pre- and postassignment assessments of self-efficacy and content knowledge (administered three times during the semester), and these studies showed that both parameters were significantly improved following each assignment. Specifically, student self-efficacy showed large gains, preassignment to postassignment (pre-post) [$F_{(1,13)} = 47.8$, $P < .001$], and content knowledge showed moderate pre-post gains [$F_{(1,12)} = 14.5$, $P < 0.002$]. Attitude surveys administered at the end of the semester suggest that the approach is seen as beneficial and enriching. We conclude that it is possible to integrate multiple levels of material in a complicated class by using storytelling and that such integration is positive and useful.

KEYWORDS undergraduate, project-based learning, cell biology, storytelling, learning gains, primary literature

INTRODUCTION

Background and rationale for transformation

Educational disciplines face the challenge of increased complexity and the dynamic nature of the material (1). The associated cognitive overload may result in confusion and decreased enthusiasm for learning, which may impact students' ability to integrate the classroom material in a coherent picture or appreciate the usefulness of the learned material outside the classroom (2). This problem may disproportionately affect students who have had less prior exposure to science due to inequities in K–12 schooling or have more concurrent demands on their time (e.g., part-time work). This problem is particularly relevant to biology education, because a very large percentage of students in the biology introductory courses are intent on pursuing medicine and other health-related fields (3). For these students, understanding the connection to applications is a strong driver that could be used to motivate much of the content. One of the most difficult aspects of cell biology education is integrating multiple levels of information into a coherent picture that highlights biomedical applications for which cell biology is an essential tool, such as cell fate, disease pathogenesis, and drug effects (4, 5). The second big challenge is demonstrating that the material described in class is relevant (6).

To address the complexity and relevance of course material in the context of biological sciences, a variety of educational approaches has been used, including addressing complexity and transforming it into a tool of discovery (7), providing simulation tools (8, 9), and using structured peer interaction (10) and collaboration (11). Creating disease-focused project-based curricula (6) and laboratory projects (12) and actively encouraging attempts to integrate material into a larger picture as a natural part of learning (2) have also been reported as ways to address complexity and emphasize the relevance of scientific material. The challenges of implementing such approaches include the specifics of the student body (background and goals), scalability, tracking, and integration into the educational process. However, recent advances in educational tools (9) and better integration of online approaches (13) provide new opportunities for project-based approaches with improved scalability and tracking as well as organic integration of primary research literature and student-based discovery.

Furthermore, we argue that the nature of the projects given to students is just as important as the tools and scaffolds

Editor Betsy M. Martinez-Vaz, Hamline University
Address correspondence to Department of Biological Sciences, University of Pittsburgh, Pittsburgh, Pennsylvania, USA, or Learning Research and Development Center, University of Pittsburgh, Pittsburgh, Pennsylvania, USA. E-mail: Kiselyov@pitt.edu or Schunn@pitt.edu.
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			Group 1	Group 2	Group 3	Group 4
			Group topic 1, eg Alzheimer's disease	Group topic 2, eg cancer	Group topic 3, eg limb development	Group topic 4, eg vision
Module number	Week number	Module content	Groups work and create posters on:			
	1	Class introduction	Groups are formed and start coordinating work on the approach			
	2-4	Protein processing, membrane traffic and quality control	Protein processing, membrane traffic and quality control in Alzheimer's disease	Protein processing, membrane traffic and quality control in cancer	Protein processing, membrane traffic and quality control in limb development	Protein processing, membrane traffic and quality control in vision
1		Discovery session 1	Poster presentations and dicussion			
	5-8	Ion transport across memranes	Ion transport across memranes in Alzheimer's disease	Ion transport across memranes in cancer	Ion transport across memranes in limb development	Ion transport across memranes in vision
2		Discovery session 2	Poster presentations and dicussion			
	9-12	Cell signaling and cell cycle	Cell signaling and cell cycle in Alzheimer's disease	Cell signaling and cell cycle in cancer	Cell signaling and cell cycle in limb development	Cell signaling and cell cycle in vision
3		Discovery session 3	Poster presentations and dicussion			
	13,14	Special chapters	Parallels and differences between Alzheimer's disease and other groups' topics	Parallels and differences between cancer and other groups' topics	Parallels and differences between limb development and other groups' topics	Parallels and differences between vision and other groups' topics
4		Discovery session 4	Poster presentations and dicussion			

FIG 1. Structure of the stories approach (left) and the assessment procedures (right).

provided to support their implementation. For courses like cell biology, the projects should inherently push students to make connections across levels and to applications. Here, we focused on expanding and strengthening the impact of project-based cell biology education by using a scaffolded approach to organizing multiple levels of information into a complete picture that develops, improves, and enriches itself over the course of the semester. We sought to integrate group activities in the workflow to improve learning and class cohesion. Active learning and primary research literature were integrated to improve ownership and demonstrate the place of material covered in class in modern science (Fig. 1). We frame this approach as creating stories, building upon Vygotsky's foundational theory of how people understand complex content (14), more recent work on the cognitive mechanisms by which students understand science through narratives (15, 16), and the success of biology and mathematics textbooks that provide in-depth narrative stories across levels and with applications (17, 18).

We performed several levels of assessment, including self-efficacy and objective knowledge gains, which were measured using pre- and postintervention surveys. Open questions were whether students would generally improve their understanding of and self-efficacy with the core course content given that they were directly engaging with the very complex primary research literature and each student group would need to learn from both their own project experience and the indirect experience of interacting with other groups' project posters.

Intended audience

This approach could be applied to a wide range of science courses where primary research literature is or can be used as part of the learning process. The activity is also beneficial in courses where integration of complex knowledge into a cohesive narrative that continues throughout the semester is important.

Learning time

The buy-in session, which involves an explanation of benefits and a discussion of examples, requires 30 min of in-class time. Each group assignment can be completed in 3 h of out-of-class work, including 1 h for discussion and planning, 1 h for individual research, and 1 h for composing, uploading, and sharing the posters. The discussion of posters (discovery session) is limited to 15 to 20 min of in-class time per group, in which individual student participation is limited to about 5 min. Four discovery sessions take place during the semester. Collectively, the approach occupies about 4.5 class sessions.

Prerequisite student knowledge

The approach involving biomedical themes and topics of this course requires general college-level biological and chemical knowledge and familiarity with modern presentation tools, such as MS PowerPoint or Google slides. Access to primary literature through the university library was essential for this course; however, other iterations of this course may rely on material available through the public domain. Formal class prerequisites to enroll in this course are the following: two semesters of introductory biology, two semesters of introductory chemistry, two semesters of organic chemistry, and one semester of either biochemistry or macromolecular structure and function (i.e., the structures and functions of proteins and nucleic acids).

Learning objectives

Participation in this approach is expected to advance students' self-efficacy and knowledge along several axes. In particular, by the end of the storytelling exercise the students should be able to (i) develop a coherent story connecting the scientific concepts discussed in each class module, (ii) explain how the concepts covered in class support the stories presented during the discovery sessions, (iii) identify the connections between the material covered in class and the modern state of research, including papers discussed in class, (iv) demonstrate improved confidence for presenting primary literature and discussing its relation to the class, and (v) develop an appreciation for the storytelling approach as a learning tool.

PROCEDURE

Faculty instructions

The approach begins with a brief in-class session that explains the project's background, rationale, and details. Students are asked to consider the continuity and relationships between different parts of the course material, as well as their relevance to current research. They are required to work on their stories in groups, incorporating figures and concepts from primary research literature and lecture material covered during each course module into online posters that are shared with the class and discussed during the discovery sessions (see File S1 in the supplemental material).

The students are shown sample posters (see Files S2 and S3), and the instructor discusses the expected level of detail, integration with classroom material, and approaches to group work.

Topic assignments and creation of the groups. The students are instructed to indicate their top three choices among possible story topics, using an online poll. The topics are shown as story titles that are focused on specific processes or diseases (e.g., cell motility or cystic fibrosis). Topics used in our approach were the following: blood pressure, cancer, cell motility, cystic fibrosis, limb development, vision, Alzheimer's disease, hearing, wound healing, heartburn, Parkinson's disease, polycystic kidney disease, mammary gland, salivary gland, and odor sensation. Student groups are created based upon topic preferences while balancing group size, with the constraints that no more than one group is assigned to each topic and groups comprise 4 to 6 students. There were 7 to 12 groups in our course. The storyline development is explicitly left to the students and unfolds iteratively across the semester to help students make the connections across molecular and organellar organization and tissue and organ functions.

Monitoring group work. Group work takes place primarily outside of class and requires no monitoring by the instructor.

Facilitating discovery sessions. Sharing and discussion of the findings occur during the discovery sessions that take place four times during the semester, at the end of each module (Fig. 1). For example, at the end of our module that is focused on protein and membrane traffic, an Odor Sensation group will present a poster about how odors and odor-sensing molecules are delivered to the cell surface and secreted, and a Cystic Fibrosis group will discuss how the cystic fibrosis transmembrane conductance regulator and the mucus components are produced and delivered.

During the first three discovery sessions, the groups present their posters, and the class discusses the progress of each story, identifies the muddiest points (19) or incomplete aspects of the stories, and advises on possible future developments in the stories. The presentations are in a conference format: groups take turns presenting and the instructor moderates the discussion, highlighting impactful points, identifying points for further discussion, and inviting questions from the audience. The instructor discusses common aspects of different stories to improve coherence in class understanding of the core ideas.

The posters are deposited online and shared with the students, and the students are encouraged to view their peers' posters. Visiting and reading peers' posters is a good individual assessment tool because it may reveal potentially impactful gaps in knowledge, which may prompt revisiting the material and closing the knowledge gaps. Furthermore, it is a good model of future professional activities and thus is useful for professional development.

Each poster is accompanied by a set of questions to the audience by the poster's authors. The questions are thought to provide an additional opportunity for analysis and learning. The students are encouraged to answer as many questions as possible, through an online form; the instructor converts students' questions into an online questionnaire, which is shared with the students shortly after the discovery session. The instructor moderates the questions to provide focus and ensure an appropriate level of detail and breadth. Each group submits five questions per session. The posters and the window for responses is open for 1 week. The responses are not timed. Approximately 60% of the students responded to our questionnaire, and each student answered 70 to 100% of the questions. Other goals of these questions are to help work with the poster and to measure participation.

The final discovery session focuses on generalizing the knowledge. Before the session, the student groups are encouraged to work on a discussion of the aspects of their stories that are similar, distinct, or complimentary to their peers' stories. The class thus has an opportunity to revisit and review the material covered during the semester.

Suggestions for determining student learning

The central idea of this class transformation is that integrating the class material into semester-long stories driven by the student groups should improve student knowledge, self-efficacy, and attitudes toward the course. Knowledge

TABLE 1
Percentages of students ($N = 55$) reporting positive, neutral, or negative attitudes toward key aspects of the approach at the end of the course

Attitude	I think that in this class I have learned useful material and concepts	Storytelling approach in general	Use of posters
Positive	81%	60%	85%
Neutral	17%	22%	11%
Negative	2%	18%	4%

gains and improvements in student self-efficacy are tested using the following combination of content self-efficacy and content knowledge measures administered before and after each in-class discussion. Attitudes toward the course are measured at the end of the course.

Content self-efficacy. Measures of self-efficacy should involve specific situations (20). Self-efficacy measures for the topics covered in this course did not exist. Therefore, student self-efficacy was measured using newly created surveys that asked about their self-efficacy with the content of each module (4 to 7 topics per module) through two specific situations applied to each topic, producing between 8 and 14 questions per module, with a 3-point Likert-type scale for each question (yes, kind of, and no) (see File S4 in the supplemental material). Exploratory factor analysis established that the two questions cohered as one overall self-efficacy factor. The reliability of the full set of items was generally good, with a Cronbach's alpha of 0.69 at preassignment and 0.89 at postassignment.

Content knowledge. Accuracy of factual knowledge was measured using multiple-choice assessments focused on basic cell biology facts associated with each story topic within each module. Again, no existing assessment tool for this content existed in the research literature, and therefore new assessments had to be created. There were between 10 and 22 questions for each of the three modules (see File S4). Each question had two or three different content options along with an "I don't know" option to reduce the noise effects of guessing, and answers were scored as 2 points for correct answers, 0.5 points for choosing and "I don't know," and 0 points for incorrect answers. Similar findings were obtained if "I don't know" was collapsed with incorrect answers. Students answered all the questions regardless of whether their project was focused on that topic or whether they were only exposed to the content via peer assessment. The reliability of each assessment was moderate, with Cronbach alphas varying between 0.49 and 0.82, as would be expected of relatively brief assessments of diverse content.

Course attitudes. To measure students' attitudes toward the course and the approach, an anonymous exit survey was used. The survey was in the form of 5-point Likert scale questions and included questions about the course overall and the storytelling approach (Table 1). The answers were then binned into 3 categories: positive, neutral, and negative. The percentage of answers in each category was used to estimate students' course attitudes.

Faculty instructions are summarized in a sample handout (see File S5 in the supplemental material).

Sample data

Groups iteratively connected module content to their overarching story. Examples of stories evolving across the semester are shown in Files S2 and S3 in the supplemental material. Some groups used a 1-page format of the posters that incorporated all components of the students' work on one large page, similar to a commonly used 3-foot by 4-foot conference poster format. Other groups submitted a set of slides telling a linear story. Many groups supplied their submission with voice narrations.

We found that in many cases the students explicitly identified sections of the posters that reflected corresponding module components (see File S2, in which protein processing and membrane traffic are on the first poster, ion transport is on the second poster, cell signaling is on the third poster, and a summary is on the last page). In other words, the "story" involves connecting the larger topic (e.g., cell biology of limb bud development) to the module topics. Other groups' posters presented a mechanistic description of components and processes involved in their topics with references to each of the module components as appropriate. The "story" in those posters was about the different components and processes contributing to the larger system functioning. A minority of posters did not have a strong storyline, as they simply presented a linear account of the research manuscript that was used to create the report.

Many posters discussed and integrated material from other groups' stories in their final presentation. In the case of the posters presented in File S3, the students focused on establishing parallels and commonalities between their and other groups' stories, as evident from explicit references to other stories presented in the final poster. There is evidence of juxtaposition and comparison of specific mechanisms and effects in the File S3 poster (e.g., contrasting saliva protein secretion with vision). Many aspects of the posters presented evidence of the integration of individual findings into a continuous narrative, as shown by the "Significance and future directions" section in poster

TABLE 2
Learning objectives and assessment instruments used to evaluate each objective and outcome

Objective	Assessment instrument
1. Create a coherent story connecting the scientific concepts discussed in each class module	Poster presentations Self-efficacy assessment Content knowledge assessment
2. Explain how the concepts covered in class support the stories presented during the discovery sessions	Poster presentations Self-efficacy assessment Content knowledge assessment
3. Identify the connections between the material covered in class and the modern state of research, including papers discussed in class	Poster presentations Self-efficacy assessment Content knowledge assessment
4. Demonstrate improved confidence presenting primary literature and discussing its relation to the class	Poster presentations Self-efficacy assessment Exit survey
5. Develop an appreciation for the storytelling approach as a learning tool	Self-efficacy assessment Exit survey

pages 2 and 3 of the File S3 poster. Therefore, we argue that the students were able to understand the place of the material covered in class in the context of modern biomedical research and to actively organize reading primary research literature in a manner that contributed to a coherent story aligning with the course's development. Furthermore, students understood key cell biology ideas and were able to interpret them in the context of modern biomedical findings.

DISCUSSION

Field testing

Course context. This storyline approach was deployed in a one-semester elective lecture class, normally taught in-person, at a large R1 public university. Data collection occurred concurrently with the class. Enrollment was between 40 and 75 students, most of whom were senior Biological Sciences majors.

Evidence of student learning

Data collection. The combined surveys of content self-efficacy and content knowledge were performed online three times during the semester, 2 to 4 days before and after each discovery session. To link pre- and postassignment survey responses in the analysis, students were asked to identify themselves and the name of their group. Participation in the surveys counted toward the participation grade. All students completed at least one combined survey, approximately 60% of students completed a given survey, and approximately 80% of the students completed at least two combined (i.e., four total) surveys. Whether students completed a survey or not was correlated near zero ($r = 0.06$) with an average postassignment knowledge score, so missing-at-random could be assumed as a good approximation.

The course attitude survey was given online at the end of the 2020 semester in an anonymous form. Eighty percent of the students completed the survey.

Overall gains preassignment to postassignment ("pre-post") in self-efficacy and response accuracy as a measure of content knowledge were assessed using simple paired *t* tests on mean pre- and postassignment scores within each survey, and Cohen's *d* was used to measure effect sizes. To follow up, a repeated-measures analysis of variance (ANOVA) was conducted to assess the consistency of the gains across years and modules with pre-post and module were within-subjects

TABLE 3
Statistical significance and effect sizes of pre-post changes in self-efficacy and accuracy within each module across all 3 years

Module	Confidence			Accuracy		
	t	*P*	*d*	*t*	*P*	*d*
1	9.05	<0.001	1.31	4.66	<0.001	0.65
2	8.71	<0.001	1.14	7.07	<0.001	0.93
3	6.44	<0.001	0.84	2.49	0.008	0.32

1.5,

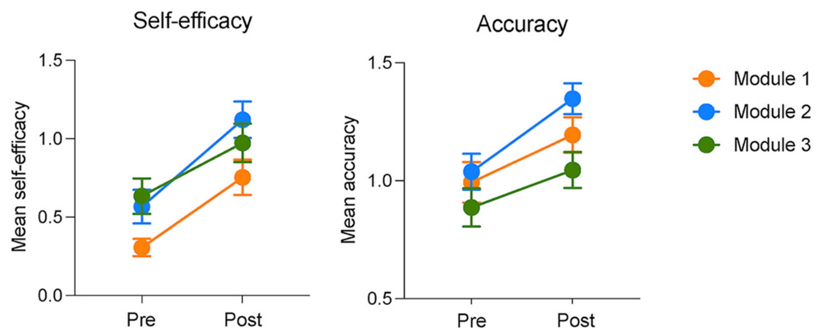

FIG 2. Pre- and postassignment means (with SE [bars]) for each module in self-efficacy (left) and content knowledge (right) measured as response accuracy.

factors and year of course offering as a between-subjects factor. To further assess the consistency of the pre-post changes by specific knowledge area, means for each given self-efficacy topic or knowledge question were calculated across all students at preassignment and then again for all students at postassignment.

Pre-post changes in self-efficacy and response accuracy. The changes in accuracy and self-efficacy support the learning objectives of the storytelling activity. Table 2 summarizes learning objectives and the assessment instruments used to evaluate each objective, as well as corresponding specific gains reported as a result of our approach.

As shown in Table 3 and Fig. 2, there were large pre-post gains in self-efficacy and more moderate pre-post changes in the accuracy within each module. All pre-post paired tests were highly statistically significant. Interestingly, module 3, which was likely the most conceptually rich and difficult module (covering cell cycle, growth, and division), had small gains in both self-efficacy and accuracy, but those pre-post changes were statistically significant, nonetheless. The repeated-measures ANOVA for self-efficacy found a significant pre-post gain [$F_{(1,13)}$ = 47.8, $P < 0.001$] but no interaction of pre-post gain by module or year ($F_s < 1$). Accuracy showed a significant main effect of pre-post gain [$F_{(1,12)}$ = 14.5, $P < 0.002$] but nonsignificant interactions of pre-post gain by module [$F_{(2,24)}$ = 1.5, $P > 0.25$] and by cohort ($F < 1$). Thus, the general patterns seem to be consistent over the years.

Figures 3 and 4 illustrate the change from the perspective of individual knowledge areas. Every single knowledge area showed general changes in self-efficacy, and 91% of students showed increases in self-efficacy. However, some knowledge assessment areas did not show growth overall in the accuracy measure from pre- to postassignment: 90% of items in module 1, 92% in module 2, and 70% in module 3 showed at least a 10% increase in student response accuracy. In addition, 67% of students showed meaningful increases in response accuracy.

Overall course attitudes. Most of the students felt they had learned useful material and concepts, liked the use of posters, and enjoyed the storytelling approach (Table 1). Very few students disagreed with having learned useful material and concepts or disliked the use of posters or did not like the storytelling approach.

Conclusions

By integrating specific aspects of the course knowledge into a continuous story, we expected to improve the understanding of the material by the students. Such integration naturally includes simple repetition, but it also includes many different kinds of constructive and

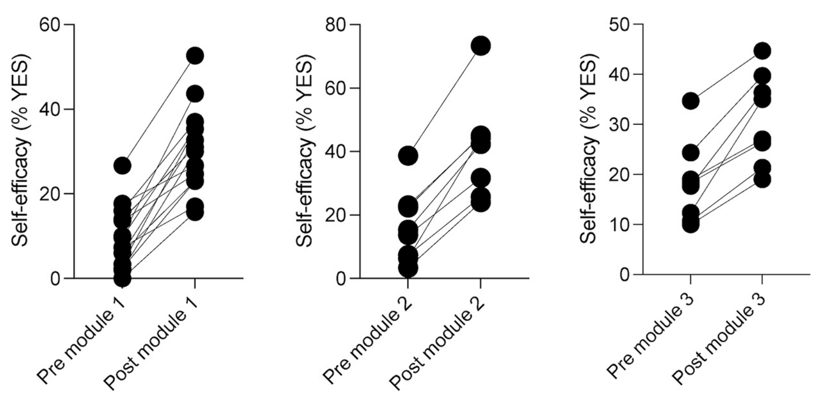

FIG 3. Percentages of students showing high self-efficacy pre- and postassignment for each specific question area, within each module, and averaged across the 3 years of data collection.

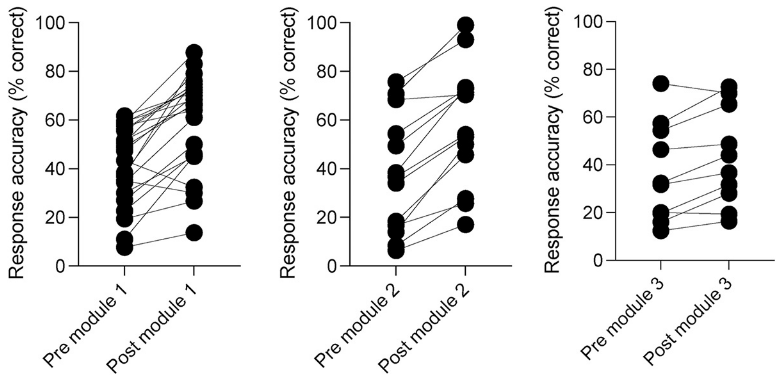

FIG 4. Percentages of students answering questions on knowledge assessment areas correctly at pre- and postassignment for each specific knowledge assessment question, within each of the modules, and averaged across the 3 years of data collection.

interactive knowledge-building activities that are particularly important for conceptual understanding of complex systems (21): collaborative design, explaining links across system levels, explaining implications for applications, evaluating and describing research evidence, summarizing and synthesizing, making connections across stories, providing constructive feedback (e.g., comments during the discovery session), and responding to constructive feedback. As a result, it is not surprising that almost all of the students improved their content knowledge after each discovery session.

The stories appear to be a promising formative assessment tool. First, this method gives the instructor a panoramic view of the entire class's development and progress and compares the performance of individual students with that of the rest of the group (using individual and group self-efficacy scores). It shows how comfortable the students are with the material discussed in class. Since each story develops during the semester, the instructor has many opportunities to evaluate the progress and pivot if necessary, and participation in the approach gives each student a readout of their progress relative to the group and other people in the class, and with it, an opportunity to refocus or seek help.

Possible modifications

The approach was tested with Biology seniors in a relatively selective research-focused institution. These students had generally experienced research through laboratory experiences and other advanced coursework, and some students had already participated in directed research. In principle, the approach is not limited to the use of primary literature, and a variant focused on a limited task of telling a complete story of a course can be applied to any discipline and student level.

We did not evaluate the quality of student posters; instead, we focused on the exchange of knowledge. However, some courses may choose self, peer, or instructor evaluation of poster quality, in which case a rubric would be recommended (for example, references 22 to 24).

SUPPLEMENTAL MATERIAL

Supplemental material is available online only.

SUPPLEMENTAL FILE 1, PDF file, 2.8 MB.

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