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Transformative Interventions in Cell Biology: The Development and Use of Instructor/Student-Interactive Demonstrations of Key Cell Biology Concepts

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In Cell Biology, a sophomore/junior undergraduate-level high-enrollment core course, students are expected to develop a broad and detailed understanding of the functioning of eukaryotic cells. For example, some of the more challenging biological concepts include machinery involved in the replication and translational processes, protein trafficking/orientation in membranes, as well as both G protein-coupled receptor and receptor tyrosine kinase signal transduction pathways. In this instructional article, we describe prior published reports of the use of interactive demonstrations of several of these key biological concepts in the classroom. Furthermore, we narrate our efforts to integrate several of these disparate evidence-based techniques (EBTs) with supplementation of our own demonstrations into a common cell biology curriculum. We have adapted these EBTs to suit large lecture classrooms (200+) as well as extended it to an online course format. We expect the hands-on nature of these learning activities will facilitate active learning of these challenging concepts in the short-term, while helping narrow achievement gaps for marginalized students, increasing student retention in majors such as Cell and Molecular Biology, and lastly for enhancing student success in post-graduate career goals over the long-term. Our overall goal is to share our own experiences deploying these approaches in-person and online that could potentially lead to a more widespread adoption of these learning props in undergraduate cell biology education as well as to stimulate research interests in evaluating the effectiveness of this unique and expanded collection of prop demonstration activities for undergraduate cell biology courses.

Individualized Student Learning

Each student's preparation for upper-level undergraduate courses in modern biology is unique. This may be mainly due to different experiential learning opportunities they have been exposed to during their formative school years as well as different levels of engagement in introductory biology courses in the early years of undergraduate education (Neitzel & Bertolini, 2019). The approaches and strategies used to learn complex scientific content also varies significantly from one student to another, and could be even a major determinant to successful learning (Juanengsih et al., 2018). While some learn by reading, other students use a combination of reading and writing (Juanengsih et al., 2018). Yet others use illustrations to learn about topics and now with the ubiquity of the web/internet, a subset of students rely on platforms like Khan Academy or videos on YouTube to learn about scientific topics (Cherif et al., 2014). In addition, some undergraduates have benefits of experiential learning through research experience that may not be accessible or available to all students (Russell et al., 2007; Sell et al., 2018; Webster & Karpinsky, 2015).

As a consequence of all of these variations in approaches alongside other factors, by the time an undergraduate student reaches the junior and senior years of their undergraduate education, their preparation for upper-level biology courses varies from having a solid foundation to being significantly under-prepared for successfully learning advanced topics. An educators' goals is to bypass these early shortcomings and expose students to the best methods of learning biology concepts that appeal to multiple senses and engage the hand, head, and the heart (three Hs of learning) to allow better comprehension and retention (Inan & Inan, 2015).

Consideration of an individual's needs and goals in the context of education creates an environment of individualized learning (Shemshack & Spector, 2020). Toward this goal, individualized learning has been shown to increase student engagement and motivation contributing to effective student learning (Shemshack & Spector, 2020). Since students come from diverse backgrounds with different characteristics, personalized instruction provides an opportunity for all students to attain their fullest potential (Shemshack & Spector, 2020). Such instruction will incorporate not only appropriate content but appropriate methods to convey this information at an appropriate pace (Shemshack & Spector, 2020). Furthermore, such personalized instruction is expected to undergo modifications with each iteration in order to account for a variety of individual differences in the student population (Shemshack & Spector, 2020). Use of technology for adaptive learning is expected to permit scalability in the number of students that would benefit and although there have been rapid advances in research on using computer technology-assisted tools and platforms for

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individualized student learning, their wide-spread adoption by faculty in the classrooms has not yet occurred (Shemshack & Spector, 2020), thus stressing the need for a rich repertoire of alternate low-tech methods in the interim.

Decreasing Achievement Gaps in STEM

Since the establishment of universities in western Europe over the past millennium, lecturing has been the common mode of instruction (Freeman et al., 2014). Over the past half a century, it has been questioned whether this traditional type of teaching is the most effective due to "pipeline" issues for students in STEM (Freeman et al., 2014). [See Appendix A for a list of abbreviations used in this article.] "Pipeline issues" refers to the diminished number of students graduating university with a STEM degree relative to the number of students initially entering with a STEM interest (Freeman et al., 2014). Although there are some published limitations with respect to integrating active learning approaches (for example, education researcher's expertise and preparation/support for instructors) (Andrews et al., 2011), a meta-analyses of 225 studies suggests improved performance on examinations for students exposed to active learning compared to those exposed to traditional lectures which was associated with increased failure rates (Freeman et al., 2014). Another meta-analysis of school education in the last decade found that changes in curriculum was one of the major factors that had significant effects on reducing the achievement gap (Jeynes, 2015). Specifically, this study concluded that social scientists may play a major role in closing the achievement gap by developing a comprehensive framework that takes into account relevant educational, psychological, and sociological factors (Jeynes, 2015).

It is reported that having "strong implementation" teachers (at school and college level) who (1) are familiar with reform curriculum, (2) use visual aids and manipulatives, (3) allow frequent group work as well as peer interactions, and (4) focus exclusively on curriculum-specific activities are very effective in improving general achievement of all students (Glover, 2017; Schoenfeld, 2002; Singham, 2003). With appropriately trained teachers, this approach would benefit all groups of students to reach rigorous threshold metrics and levels of proficiency as compared to students taught by instructors lacking such characteristics (Glover, 2017; Schoenfeld, 2002; Singham, 2003). Therefore, sustained professional development and support of teachers is singularly important in fulfilling the goal of high achievement by all students; this includes training teachers with "generic teaching skills" conducive to "active learning" that include organizing well-structured cooperative classrooms, implementation of hands-on and inquiry-based learning assignments, promoting intrinsic motivation in students, designing challenging course content, and supporting student success (Singham, 2003).

Although traditional lecturing may be thought of as the most efficient for large enrollment classes, the limited interaction between students and student-instructor may result in superficial learning with low levels of student motivation and enthusiasm toward the course content (Armbruster et al., 2009). The negative outcomes leaves students lacking important skills for success in the job market (Armbruster et al., 2009). Therefore, a change in approach toward student-centered strategies to support learners' problem solving skills, critical thinking skills, and deep learning would be more meaningful toward a diverse student body (Armbruster et al., 2009). Students must therefore be placed at the "center of instruction" to enable a shift of learning, away from the traditional way of teaching. Promotion of active learning approaches has since led to the establishment of (1) national programs supporting this cause, (2) journals such as *Cell Biology Education–Life Sciences*, and (3) databases of active learning strategies (Armbruster et al., 2009). A research study incorporating such active learning approaches in a large enrollment introductory biology course resulted in positive results including improvements in student attitudes and their academic performance in the class (Armbruster et al., 2009).

Students' background is varied in the classroom not only in terms of their educational focus but also life experiences, background knowledge, cultural intelligence, and ability to tackle challenges; indeed, all of these elements can affect their educational success (Riestra et al., 2019). Disparity in academic achievements is documented in those from socioeconomic disadvantaged backgrounds particularly in high school students (Betancur et al., 2018). However, these disparities occur early, as reported in recent study focusing on children attending elementary and middle school with gaps in science achievements related to household income and parental education (Betancur et al., 2018). It is well established that disparity in academic achievements in STEM specifically persists in underrepresented groups (URGs) (Riestra et al., 2019) as well as transfer students from community colleges.

Factors that can combat this disparity to improve their academic performance include class projects that foster student inclusiveness, confidence, and community in the classroom (Jordt et al., 2017; Riestra et al., 2019). Such projects include low-stakes, in-class assignments and group work in addition to the

heavily weighted examinations (Riestra et al., 2019). Importantly, evidence supports high-intensity, student-centered, active learning strategies in diminishing these URG performance disparities and enabling their success toward a STEM degree (Jordt et al., 2017; Theobald et al., 2020). Thus, innovations in such student-centered active instructional strategies may remediate the URG disparities, leading to improved equity in STEM performance.

Of particular relevance to our instructional goals herein, Theobald and colleagues (2020) emphasize the use of high-intensity, in-class student tasks and stepwise exercises to address misunderstandings in key concepts whilst providing immediate instructor-driven feedback and providing time for students to practice while supporting intellectual growth and success. Although overall active learning will enable improved comprehension of course material, in biology courses, there appears to be a positive association between clarification of misconceptions with active learning (Burke et al., 2020).

Cell Biology, a Core Cell, and Molecular Biology Course

In this sophomore/junior undergraduate-level high-enrollment core course at the University of South Florida, Tampa, students are expected to develop a broad and detailed understanding of the functioning of eukaryotic cells. Specifically, this course expands on their first-year biology course beyond general biochemistry and biomolecular function including topics such as organization and function of biological membranes, basic principles of small molecule transport across biological membranes, organization of the cytoskeleton, DNA replication, transcription, translation, gene regulation, protein transport, cell communication, and the cell cycle. To individualize student learning of the previously described challenging cell biology concepts, we review published educational efforts involving demonstrations/props and supplement it with our own tools with the goal to accelerate and deepen student learning by addressing students' needs more individually to therefore decrease achievement gaps (i.e., such as those in URGs and students transferring from community colleges). Props are defined herein as physical objects and tools that are made from various, easily accessible materials to represent components of cellular and molecular processes. These props are used to enact biological events with the goal to provide students with the spatial and temporal comprehension of biological processes. Furthermore, beyond the first iteration using these demonstrations/props, students also engaged in creating smaller scale props in class-based group projects.

Method

Educational Prop Toolbox of Challenging Cell Biology Concepts

Overview

The standard textbook utilized for this class (from which our innovative pedagogical tools are discussed next) is *Essential Cell Biology* by Bruce Alberts (Alberts et al., 2019). Each year at our institution, roughly four or five face-to-face sections of the cell biology course use this textbook, whereas one online section uses Karp's Cell and Molecular Biology (Karp et al., 2016). Both textbooks include sections of various cell biology processes supported with illustrations. The still images are heavily used for instructional purposes by all instructors teaching this course. Based on our own experience, there is a tendency to rely less on any publisher-provided videos since these are fewer and somewhat more challenging to share with students during in-class instruction, and usually tend to be shared out of class only.

DNA replication, protein synthesis, protein orientation, and cellular signaling are all challenging concepts for students in cell biology classes. Prior independent review board-approved studies have demonstrated that three-dimensional prop demonstrations of the most challenging biological concepts facilitate student performance compared to traditional lectures alone (Tamari et al., 2015). These demonstrations, accompanied by a short traditional lecture, support a better understanding of complex mechanisms and enable long-term retention of concepts (Tamari et al., 2015). Further, evidence supports positive students experiences and learning mediated with kinesthetic activities involving props (which are both physically and intellectually engaging interactive activities) in combination with writing assignments (Tamari et al., 2015). Moreover, the availability of such props outside of the classroom further facilitates student understanding (Tamari et al., 2015) by providing additional hands-on time both alone and with peers. Such experiences can provide an advantage particularly for students who are not as prepared for biology courses or for whom English is a second language (Polizzotto & Tamari, 2015).

Based on these established good practices, we initially developed one complete set of instructor-usable props for DNA replication, protein synthesis, and cell signaling (four separate signaling cascades). One instructor-usable prop along with six student-usable props were also developed to engage students in concepts pertaining to protein trafficking/membrane orientation. The props and their implementation were either adapted and modified from those reported in

separate publications (described as follows) or were developed from scratch.

DNA Replication

In DNA replication, common student misconceptions include the number of forks per origin of replication, the directionality of fork movement, and the locations of the leading and lagging strands. Thus, to address these, we developed a unique prop for DNA replication, shown in Figure 1A. The prop included essential components of the replication bubble such as the origin of replication, direction of the forks, and various enzyme and non-enzyme activities. These components were displayed in stepwise progression. The components were created out of glitter poster board attached to a sponge-like material (representing the replication bubble, for pinning). The various components were attached as they were being described, while also drawing out the process in a stepwise fashion and displayed using a document camera (Figure 1A and 1B).

Protein Synthesis

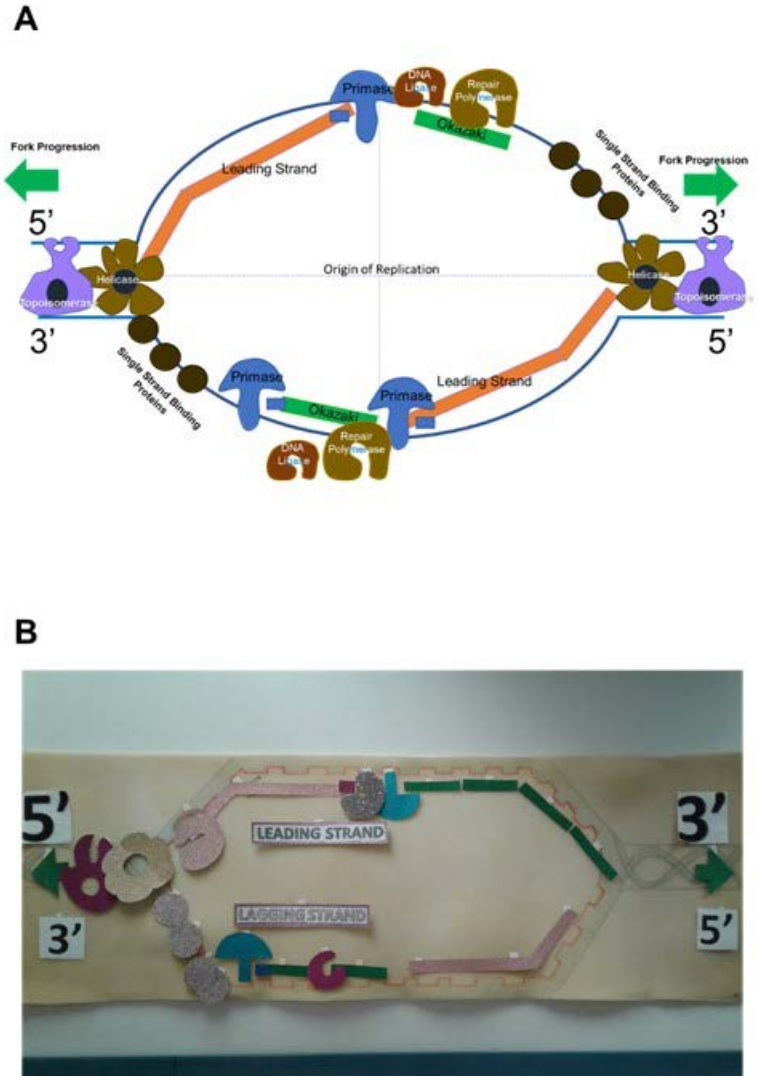
Protein synthesis is another challenging three-dimensional process which students struggle to fully understand and visualize in real-time. During the process of translation, the initiator tRNA (attached to methionine or Met) is bound to the P site of the small ribosomal subunit. This subunit then binds to the 5'-cap of the mRNA and scans the mRNA for the start AUG codon. The large ribosomal subunit subsequently binds to the complex. Elongation of translation occurs when an incoming aminoacyl-tRNA (charged with glycine or Gly, for example) arrives at the A site. This is followed by peptide bond formation between the Met and Gly via the peptidyl transferase activity of the large ribosomal subunit, and the peptide chain is transferred simultaneously to the A site. The large and small ribosomal subunits move over one codon unit, whereby the growing polypeptide chain is now in the P site and the A site is now free to accept the next incoming aminoacyl-tRNA; the elongation process then continues. The prop developed by Polizzotto and colleagues engages students directly with tRNA molecules that bring incoming amino acids (on pens) to the ribosomal subunits (Polizzotto & Tamari, 2015). Such a demonstration actively engages students to promote their learning.

Common misconceptions or challenges include locating the position of the growing polypeptide upon peptide bond formation and the position of incoming tRNAs, both of which reside in the A site. Thus, to address these, we developed a Protein Synthesis Prop, where the A, P, and E sites were created from large glitter poster board which we attached to a rolling white board found in the classroom. We added amino acid names to markers (which were attachable) to represent a growing polypeptide chain. We also created the release factor using glitter poster board. We had a series of student volunteers come to the front of the classroom to represent incoming tRNAs charged to an amino acid. We went through the joining of five separate amino acids so the process was repetitive to the students to both illustrate the iterative nature of the process as well as to reinforce learning. We moved the rolling white board (representing the large and small ribosomal subunit) after each peptide bond was formed (Figure 2A and 2B).

Protein Translocation and Orientation

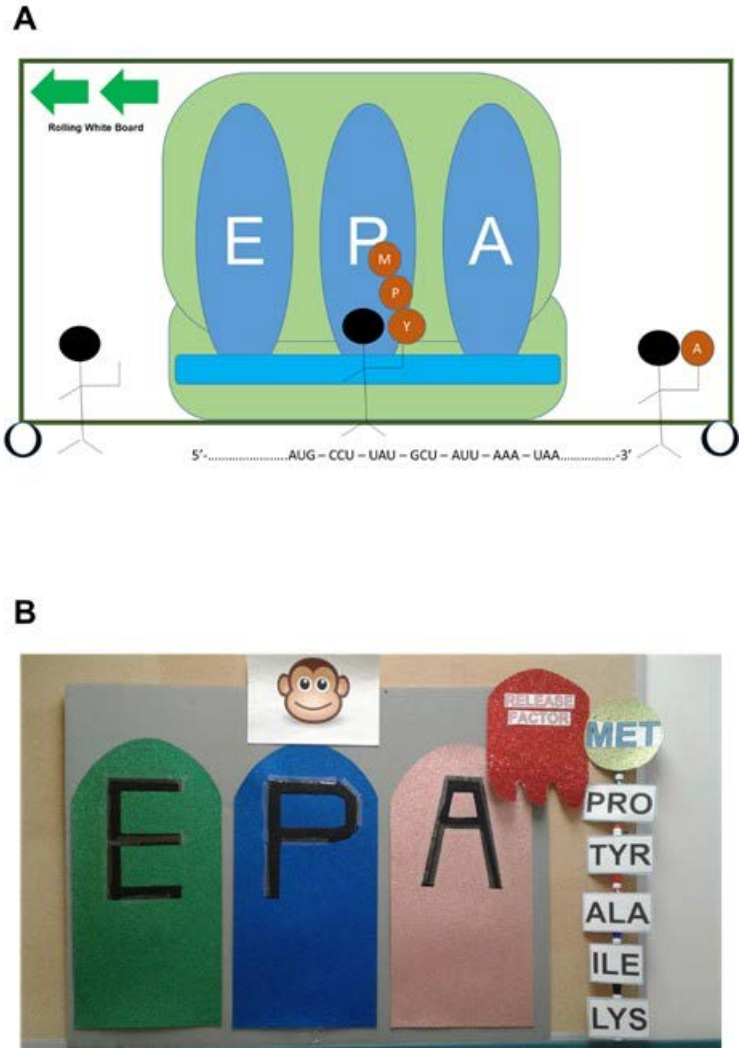
Another challenging concept in biology is protein translocation and orientation within biological membranes, notably the endoplasmic reticulum (ER), their site of construction. Indeed, Labonte (2013) reported the use of a demonstration that utilized modeling clay as a learning kinesthetic tool to simulate this biological process. In this kinesthetic assessment, Labonte (2013) reported that students demonstrated improvements in solving problems to predict protein orientation in the ER membrane. During protein synthesis, for a growing polypeptide to be targeted to the ER and associate with its membrane, a complex pattern of signal sequences within the polypeptide chain must be recognized and deciphered by cells. During the process of mRNA translation, a hydrophobic stretch of amino acids at the N-terminal or internal region is identified and bound by the signal recognition particle (SRP). This binding stops the translational process momentarily until SRP brings the ribosomal complex (with mRNA and partially translated protein) to the SRP receptor on the ER membrane. Subsequently, this complex shifts over to the ER translocation channel (enabling binding of the hydrophobic stretch of amino acids to the channel) and the translation process resumes. Once translation is complete, the N-terminal ER signal sequence is cleaved by an ER localized signal peptidase, thereby regenerating a new N-terminal end and releasing the protein into the ER lumen (if no other ER signal sequences are present). Such proteins can then move forward in the anterograde direction toward the Golgi apparatus and further on via vesicular trafficking, should there be exit signals/or lack of retention signals (e.g., KDEL motifs). For transmembrane proteins, internal ER sorting signal sequences are never cleaved by signal peptidases and thus, these segments become membrane spanning and may be retained within the ER if retention signals are present (e.g., KKXX motifs). Apart from the modeling clay tool, students were taught to approach the problem via other methods since modeling

Figure 1
DNA Replication Prop



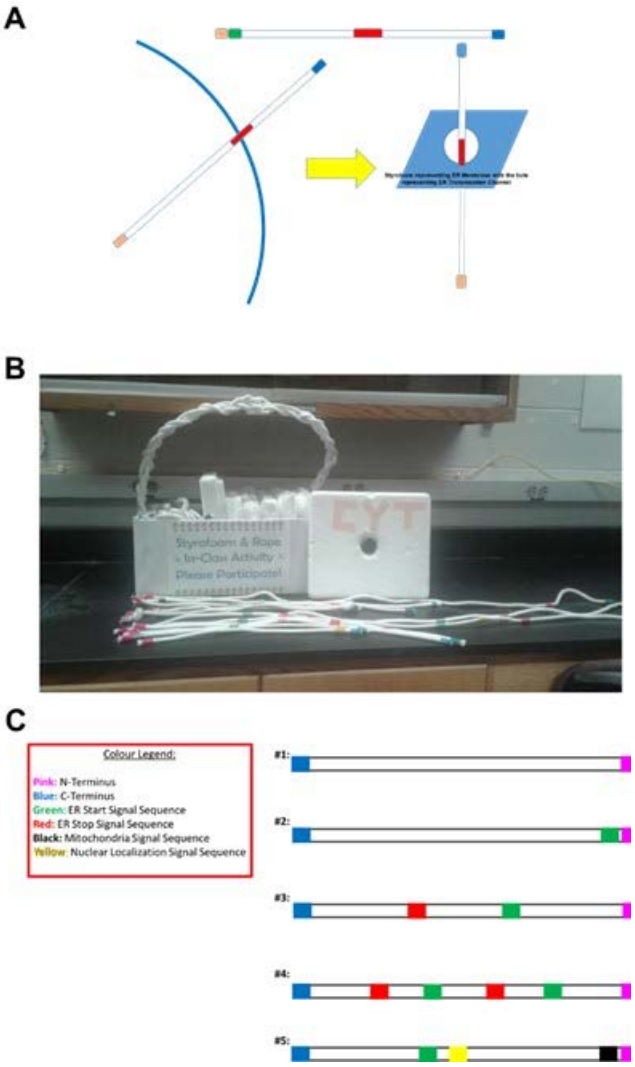
Note. (a) Prop components adapted from *Essential Cell Biology*, fifth ed., Chapter 6 (Fig. 6-20), demonstrating the production of the continuous and discontinuous strands involving the various enzymatic and non-enzymatic components of the replication machinery including helicase, topoisomerase, single-stranded binding proteins, primase, DNA repair polymerase, and DNA ligase. (b) The props made from glitter paper and Styrofoam showing all of the main components of the replication machinery. Adapted from the *Essential Cell Biology,* fifth ed., by Bruce Alberts et al.

Figure 2
Protein Translation Prop



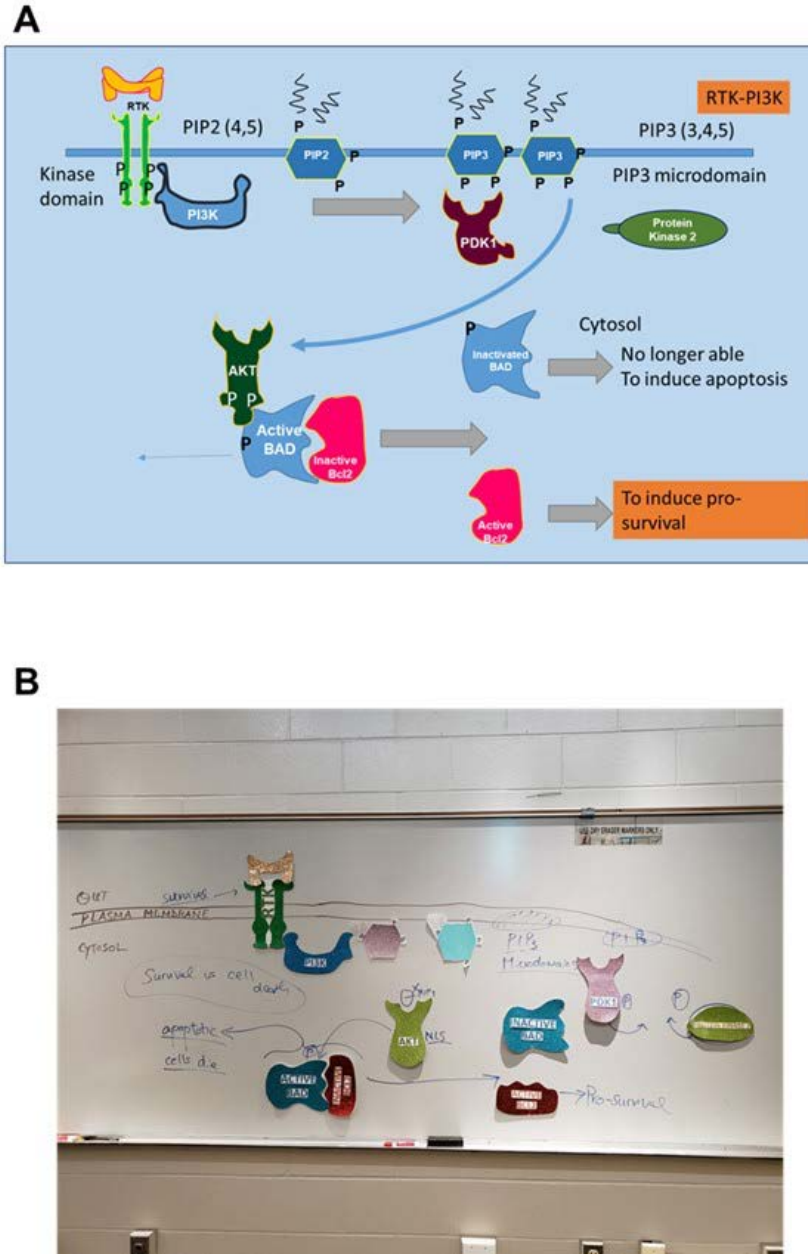
Note. (a) A PowerPoint depiction of the prop components (developed from Fig. 7-37, *Essential Cell Biology*, fifth ed., Chapter 7), demonstrating the translation of an mRNA sequence involving the large and small ribosomal subunits, activated tRNAs. (b) The props made from glitter paper attached to a rolling white board, which simulated the large and small ribosomal subunits moving in real-time with students as incoming tRNAs attached to amino acids (clickable markers). Adapted from *Essential Cell Biology,* fifth ed., by Bruce Alberts et al. Copyright© 2019 by Bruce Alberts, Dennis Bray, Karen Hopkin, Alexander Johnson, the Estate of Julian Lewis, David Morgan, Martin Raff, Nicole Marie Odile Roberts, and Peter Walker. Used with permission of the publisher, W. W. Norton & Company, Inc. All rights reserved.

Figure 3
Protein Orientation Props



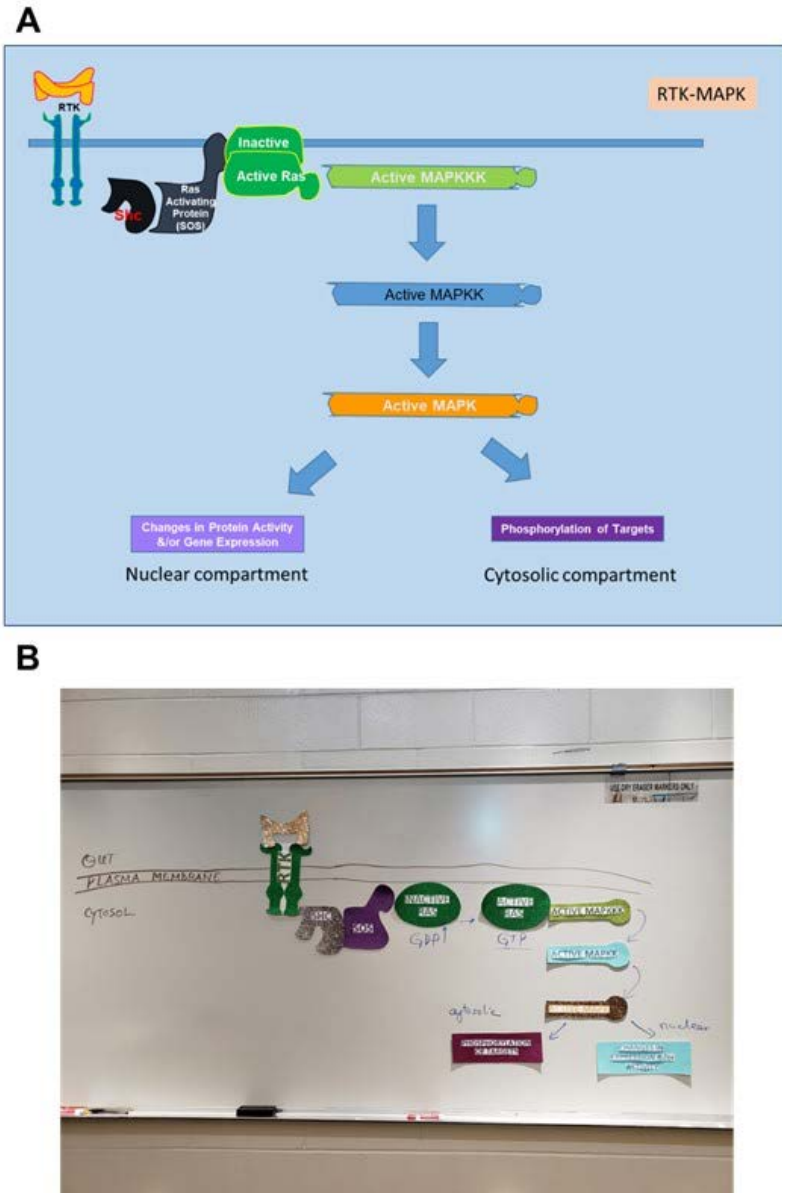
Note. (a) Prop components were developed from *Essential Cell Bio*logy, fifth ed., Chapter 15 (from Fig. 15-15, 15-16, and 15-17), demonstrating the orientation of the proteins within the ER membrane. (b) To develop the prop, the proteins containing various sorting signals were represented by ropes with multi-colored tapes and the ER translocation channel was represented by a hole cut out in a Styrofoam box top. (c) A subset of protein models for student practice of protein orientation. Adapted from *Essential Cell Biology,* fifth ed., by Bruce Alberts et al.

Figure 4.
Signaling Cascade Props



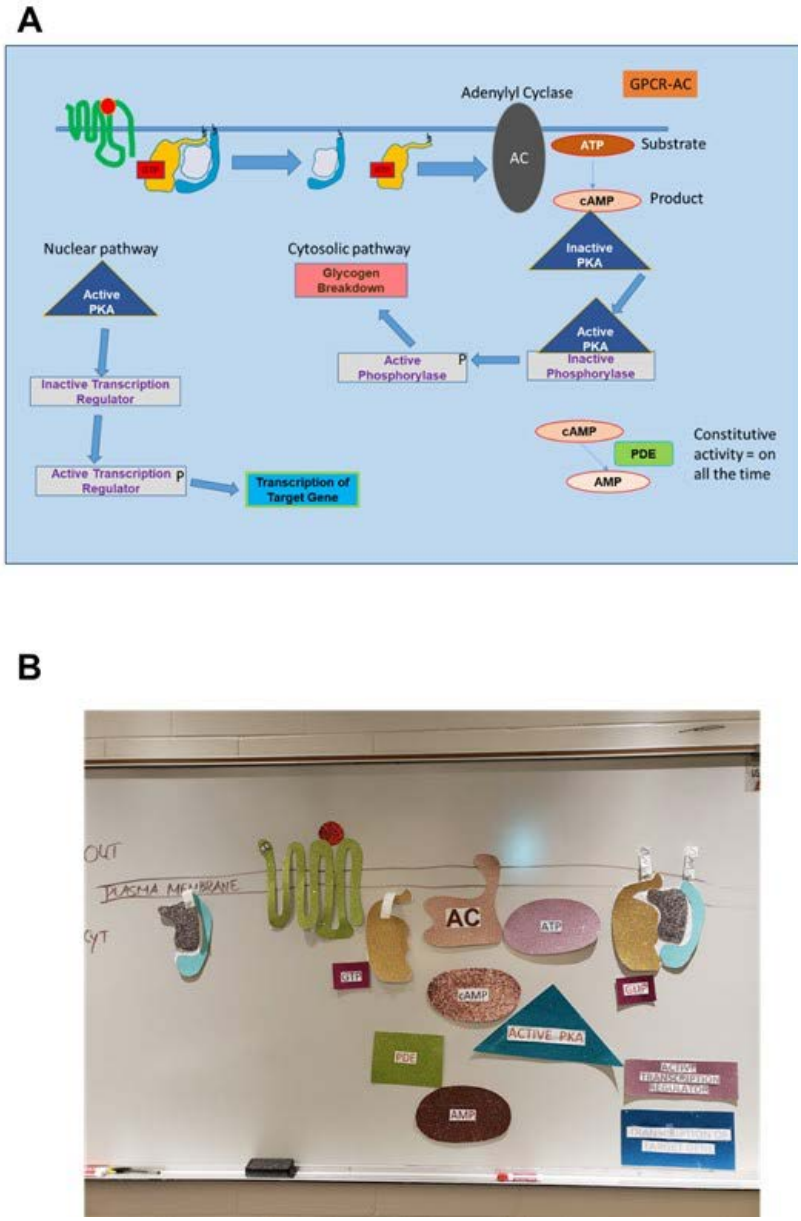
Note. (a) PowerPoint-made depiction of relevant signaling pathway components adapted from *Essential Cell Biology*, fifth ed., Chapter 16 (from Fig. 16-32 and 16-33). (b) The physical props based on Panel A made from glitter paper and attached to the whiteboard, as movable components. Adapted from *Essential Cell Biology,* fifth ed., by Bruce Alberts et al. Copyright© 2019 by Bruce Alberts, Dennis Bray, Karen Hopkin, Alexander Johnson, the Estate of Julian Lewis, David Morgan, Martin Raff, Nicole Marie Odile Roberts, and Peter Walker. Used with permission of the publisher, W. W. Norton & Company, Inc. All rights reserved.

Figure 5.
Signaling Cascade Props



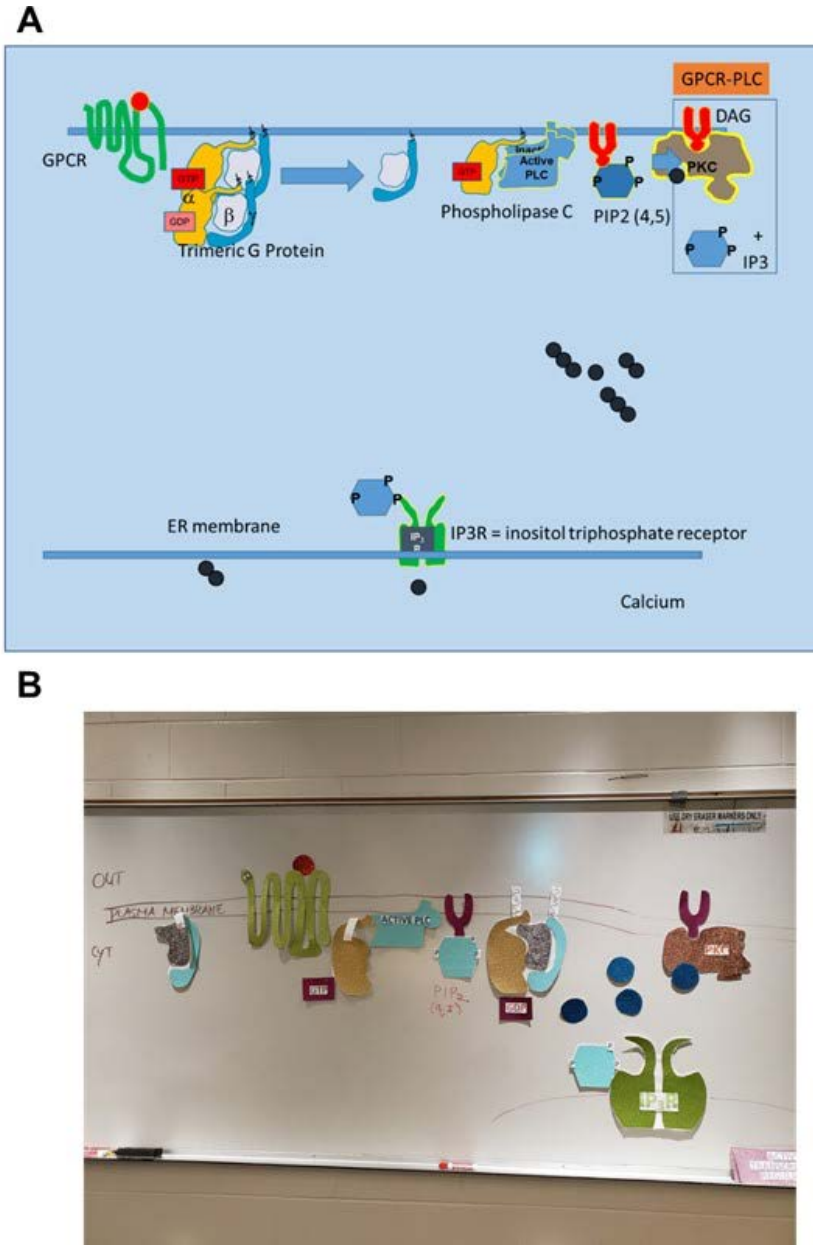
Note. (a) PowerPoint-made depiction of relevant signaling pathway components adapted from *Essential Cell Biology*, fifth ed., Chapter 16 (from Fig. 16-30 and 16-31). (b) The physical props based on Panel A made from glitter paper and attached to the whiteboard, as movable components. Adapted from *Essential Cell Biology,* fifth ed., by Bruce Alberts et al. Copyright© 2019 by Bruce Alberts, Dennis Bray, Karen Hopkin, Alexander Johnson, the Estate of Julian Lewis, David Morgan, Martin Raff, Nicole Marie Odile Roberts, and Peter Walker. Used with permission of the publisher, W. W. Norton & Company, Inc. All rights reserved.

Figure 6.
Signaling Cascade Props



Note. (a) PowerPoint-made depiction of relevant signaling pathway components adapted from *Essential Cell Biology,* fifth ed., Chapter 16 (from Fig. 16-21 and 16-22). (b) the physical props based on Panel A made from glitter paper and attached to the whiteboard, as movable components. Adapted from *Essential Cell Biology,* fifth ed., by Bruce Alberts et al. Copyright© 2019 by Bruce Alberts, Dennis Bray, Karen Hopkin, Alexander Johnson, the Estate of Julian Lewis, David Morgan, Martin Raff, Nicole Marie Odile Roberts, and Peter Walker. Used with permission of the publisher, W. W. Norton & Company, Inc. All rights reserved.

Figure 7.
Signaling Cascade Props



Note. (a) Powerpoint-made depiction of relevant signaling pathway components adapted from Essential Cell Biology 5th Edition, Chapter 16 (from Fig. 16-23). (b) the physical props based on Panel A made from glitter paper and attached to the whiteboard, as movable components. Adapted from the fifth edition of *Essential Cell Biology,* by Bruce Alberts et al. Copyright © 2019 by Bruce Alberts, Dennis Bray, Karen Hopkin, Alexander Johnson, the Estate of Julian Lewis, David Morgan, Martin Raff, Nicole Marie Odile Roberts, and Peter Walker. Used with permission of the publisher, W. W. Norton & Company, Inc. All rights reserved.

Table 1.
Summary of Variations in Format and Assessments Possible for Utilization of Props in Cell Biology Courses

Iteration (Semester)	Format	Administration of Demos/Props	Student Participation/Assessments
Iteration #1 (Fall 2018)	In-Class	Instructor demonstration of processes utilizing props	In-Class Student Participation with Props & In-Class Problem Set
Iteration #2 (Fall 2019)	Online	Templates in pdf format and instructions provided online for group project.	Group project to submit YouTube videos utilizing the props.
Iteration #3 (Spring 2020)	In-Class	Student-developed props were made available for student use	In-Class Student Participation with Props & In-Class Assignment
Iteration #4 (Fall 2021)	In-Class	Instructor demonstration of processes utilizing props	In-Class Problem Sets & Group Assignments as Short Essays
Iteration #5 (Spring 2022)	In-Class	Instructor demonstration of processes utilizing props	In-Class Student Participation with Props, In-Class Problem Set, & Independent Student Quizzes

clay would not be available for examinations (LaBonte, 2013).

For our ER Protein Trafficking Props, we created six sets of ER protein trafficking props for student use. In each set, there were in total 14 separate rope-problems for the students to understand and solve (with and without ER retention signals such as KDEL and KKXX motifs). We color coded sorting signals using tape on the ropes and cut out an ER translocation channel usingStyrofoam lids (from packaging boxes). As this process was demonstrated to students, it was simultaneously drawn out on paper and displayed by the document camera (Figure 3A, 3B, and 3C).

Signaling Pathways

Signaling pathways are yet other challenging concepts to teach due to the large array of events and new terms for memorization together with generalized core concepts across multiple pathways (MacDonald et al., 2019). A "constructivism" approach was recently described by MacDonald and colleagues (2019) which stimulated students in a student-centered learning approach to develop their own foundational signaling pathway based on specific categorization of pathway levels (along with writing a narrative), rather than specific pathways to enable understanding of how signals integrate (e.g., phosphorylation and molecular interactions leading to altered cellular outcomes) (MacDonald et al., 2019). In this approach, students were required to create, synthesize, and apply the learned information on generic knowledge acquired of cellular signaling (MacDonald et al., 2019). As described in Figure 16-9 in Alberts et al. (2019), such generic signaling pathways involve an extracellular signal molecule (e.g., ligand) which binds to a transmembrane protein (e.g., receptor protein) on the cell surface. This binding event conveys a change in conformation in the receptor protein leading to phosphorylation events in the intracellular side of the receptor. These phospho-sites create docking points for downstream adaptor molecules enabling a "relay" of signals that involve transducers and amplifiers generating second messengers that subsequently activate downstream enzymes that then phosphorylate/activate other molecules to distribute the signal. The functional outcomes of such a relay of signals include altered metabolism, altered cell shape or movements, as well as altered gene expression patterns.

For our Signaling Cascade Props, we created four specific signaling pathways (transducing signals from the plasma membrane to the cytosol or nuclear compartment): (a) RTK-PI3K/AKT cascade (Figure 4A and 4B), (b) RTK-MAPK cascade (Figure 5A and 5B), (c) GPCR-adenylyl cyclase-protein kinase A cascade (Figure 6A and 6B), and (d) GPCR-phospholipase C-protein kinase C cascade (Figure 7A and 7B). These props were created out of glitter poster board and pinned to white boards as they were being described (in order of events). These were made accessible to the class students to take photographs and practice with them toward their examination preparation. By using cut-outs representing molecules with approximate complementarity of shapes that students can handle, it is further possible to convey the idea that biological processes are based on physical interactions between molecules. Also, the fact that these processes may be transient and binding of

molecules to each other may be reversible, makes our props an ideal tool for students to appreciate the dynamic nature of biological processes.

Results

Sample Assessments to Moderate Demonstrations

Overview

Our efforts to moderate demonstrations are summarized across five iterations of a Cell Biology college course from Fall 2018 until Spring 2022 in Table 1. We discuss our efforts in detail so future educators can easily adopt our strategies and tailor them if necessary to meet their specific classroom goals; and for those educators engaged in classroom-based research, to potentially conduct well-defined IRB research studies to address effectiveness of these innovative approaches.

First Iteration

The development and initial use of these props in Fall 2018 made the Cell Biology class more exciting from our instructional perspective. Instructor-driven demonstration of the cellular processes using props with follow-up problem sets for students to solve, encouraged us to consider the refinement and long-term implementation of this approach in future semesters. Students were also enrolled in an independent study course in a subsequent semester to help develop greater number of *Student-Usable Props* which would then be utilized by future cell biology students for in-class activities.

Second Iteration

In Fall 2019, we utilized student-driven prop-based activities with graded components in an online version of the Cell Biology course. In a minor modification from our original strategy, templates were provided to students in this online Cell Biology course to print, cut out and use for making their own props, followed by creating YouTube videos to demonstrate the relevant cellular process using the correct assembly of prop components. Students were required to assemble the props in groups, then re-enact the assembly for the YouTube video which they submitted as the graded assignment component for this online course. With the assistance of two course teaching assistants (TAs), we developed a list of project instructions for the students and scanned glitter board cut-outs of molecular shapes such as proteins (the props used for scanning were from student-use prop sets created by a cohort of independent study students originally meant to be used for in-class activities in face-to-face cell biology courses in future semesters). We shared these resources with all of the students in the online course through the Canvas learning management system (LMS). In this online course, 229 students were assigned into groups of five and each group was assigned one of the six possible projects discussed previously. For convenience of collaboration times, some regrouping into smaller groups was permitted to accommodate time constraints of individual students. For two of the six projects (protein trafficking and DNA replication), we also provided additional instructions in pdf format for rope sizes representing the primary structure of proteins, images with marked positions of colored tapes representing the various localization signals in proteins, as well as the structure of a DNA replication bubble on a foam background. In this format, students in each group were required to purchase these materials in a collaborative manner and create the cut-outs on colored glitter board using the templates provided through the Canvas LMS.

Since the online course occurred in a semester just before the COVID-19 pandemic, it included mandatory weekend on-campus exams offering the opportunity for students to spend 3–4 hours together to complete this assignment. Then they were required to make YouTube videos and share the link of their videos in an assignment (1% of total grade) that was graded with equal emphasis on completion as well as for quality/accuracy. Students were also required to submit their cut-outs and other props for use in future courses (2% of the total grade), and this component was also graded with equal emphasis on completion as well as for precisely matching with the online templates that were provided previously through the Canvas LMS.

Such student-driven exercises with flexible options for the project assignment can often lead to unexpected innovations that may be instructional for the instructors involved as well. Some student groups in the previously described cohort decided to use PowerPoint stills with narration instead of live video demonstration of the cellular processes using the props. We embraced this creative idea and adopted it in another of our senior-level biology courses (developmental biology) during the COVID-19 pandemic, wherein we asked students to create shapes in PowerPoint, animate developmental processes, and make YouTube videos (prior to this, students in developmental biology were required to use colored clay, work closely in groups and make YouTube videos of developmental process, a task that was impossible to carry out during the peak of the COVID-19 pandemic). This modification of a remote, online collaborative PowerPoint-YouTube project could be useful in online cell biology courses or other online courses, particularly if there are no mandatory meetings on the university campus or during future peaks of the COVID-19 pandemic that would force remote instruction.

Third Iteration

In Spring 2020, we administered an in-person format student discussion group prop. We ran a single in-class assignment for an *in-person format* Cell Biology course just prior to the transition to remote course delivery due to the COVID-19 pandemic, our first iteration of our target goal of student-student/discussion group learning using the tactile/visual prop tools. This exercise utilized the *student-usable* DNA replication props.

For this large lecture course of 201 students, we created 28 total groups: 23 groups of seven and five groups of eight students. Two teaching assistants/graders assisted us with this DNA-replication prop activity in this *in-person* Cell Biology course. To accommodate a limited workspace in the lecture hall and nearby areas, we divided the groups into two sections and ran one section in the first half of one 75-minute lecture, and the second section in the last half. The groups were assigned to three specific areas and classrooms in and around the lecture hall. While one section completed the exercise, the other attended lecture. Lettered placeholders were used to mark the spot within or without the lecture hall where each group was assigned to work. To fit into half of a 75-minute lecture period (~30 minutes), we utilized an assignment that focused on the mechanics and orientation of strand synthesis at each fork, as opposed to protein assembly in the instructor-use prop.

The DNA replication in-class assignment (see Figure 8) was a group exercise consisting of eight questions totaling 1 point (1% of the final course grade), to be worked in collaboration with each student's groupmates, and to be completed and submitted by each student electronically through the Canvas LMS. This in-class assignment had two components, a practical component worth 0.4 points (items #1 and #2) and an electronic component worth 0.6 points (items #3–#8). The assignment questions lacking answer choices were distributed one lecture prior to the exercise, to allow students to independently consider all of the items in a leisurely fashion, prior to class. The assignment questions with answer choices were provided on the day of the assignment. Students worked in groups in their assigned spaces, supervised by the teaching assistants, and submitted their answers electronically within the course period. Overall student performance on this in-class assignment averaged 90%. And once again, student evaluative comments on the course evaluation tool at end of semester were positive.

Fourth Iteration

In Fall 2021, using a combined in-person/Microsoft Teams platform iteration (i.e. hybrid classroom due to COVID pandemic), a cohort of ~140 enrolled students were integrated into student workgroups (with 5–6 students per group). A combination of instructor-driven student-learning with student-student/discussion group learning using the tactile/visual prop tools was implemented. We utilized a third-party clicker platform (TopHat) and a graded in-class assignment (questions are presented in Table 2) that required observation of the class demonstrations.

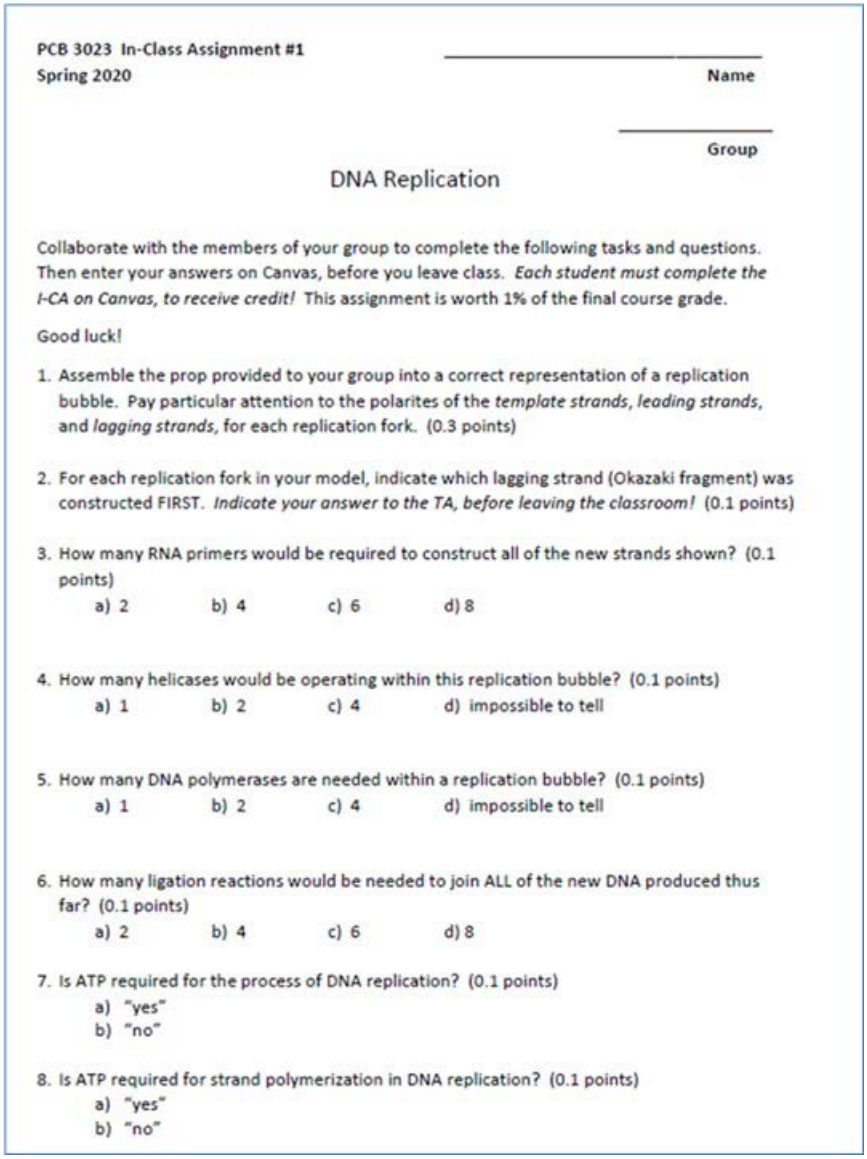
Fifth Iteration

In the latest combined in-person/MS Teams platform iteration in Spring 2022, we again utilized a third-party clicker platform (TopHat) for graded in-class assignment questions as well as independent-graded Canvas quizzes that both required observation of the class demonstrations. Furthermore, an independent review board-approved protocol to acquire survey data was approved and implemented in this last iteration although we will not present any empirical data pertaining to effectiveness of our approach in this instructional article. Instead, please refer to Table 3 for sample student anonymous responses to a survey.

Discussion

We anticipate that our efforts to review the utilization of props in biology courses from existing literature on classroom teaching, together with a narration of our own efforts to consolidate, innovate, and implement such tools in undergraduate cell biology courses, will serve as a useful resource for instructor colleagues elsewhere. We hope wider adoption of these facile strategies will enable student success in cell biology as well as improve student retention in the Cell and Molecular Biology major. Beyond the coursework for the CAM major, through these innovative prop-based approaches, we aim to support student success in post-graduate goals including success on MCAT-type essay/data analysis questions and in post-graduate research goals. We also expect that this effort applying evidence-based approaches in the classroom will have a positive impact on transforming the teaching culture, which will enable better student learning experiences and improve retention of students in the Cell and Molecular Biology degree. These teaching innovations are expected to have wider consequences by promoting continuous educational improvement across a wide array of core courses, in addition to promoting high-quality teaching and professional development for our faculty and graduate teaching assistants. Individualized student learning using the proposed EBT in high student enrollment courses

Figure 8.
Iteration 2: Eight-Question Assignment



PCB 3023 In-Class Assignment #1
Spring 2020

Name _____

Group _____

DNA Replication

Collaborate with the members of your group to complete the following tasks and questions. Then enter your answers on Canvas, before you leave class. *Each student must complete the I-CA on Canvas, to receive credit!* This assignment is worth 1% of the final course grade.

Good luck!

1. Assemble the prop provided to your group into a correct representation of a replication bubble. Pay particular attention to the polarites of the *template strands*, *leading strands*, and *lagging strands*, for each replication fork. (0.3 points)

2. For each replication fork in your model, indicate which lagging strand (Okazaki fragment) was constructed FIRST. *Indicate your answer to the TA, before leaving the classroom!* (0.1 points)

3. How many RNA primers would be required to construct all of the new strands shown? (0.1 points)
   a) 2 b) 4 c) 6 d) 8

4. How many helicases would be operating within this replication bubble? (0.1 points)
   a) 1 b) 2 c) 4 d) impossible to tell

5. How many DNA polymerases are needed within a replication bubble? (0.1 points)
   a) 1 b) 2 c) 4 d) impossible to tell

6. How many ligation reactions would be needed to join ALL of the new DNA produced thus far? (0.1 points)
   a) 2 b) 4 c) 6 d) 8

7. Is ATP required for the process of DNA replication? (0.1 points)
   a) "yes"
   b) "no"

8. Is ATP required for strand polymerization in DNA replication? (0.1 points)
   a) "yes"
   b) "no"

Table 2.
Summary of Iteration #4 Essay Questions

PCB3023 Unit Material	Sample Group Assignment Questions
Unit II: DNA Replication, Transcription, Translation, and Gene Regulation	1. Explain in your own words the process of DNA replication (step-by-step with details) 2. Explain in your own words the process of RNA transcription (step-by-step with details) 3. Explain in your own words the process of Protein Translation (step-by-step with details) 4. Problem-Solving: Mutation in DNA sequence, determine transcript, and protein products 5. Problem-Solving: Regulation of Gene Expression involving repressors and activators
Unit III: Protein Trafficking and Orientation	1. Describe mechanism of protein import into the ER, mitochondria, and nuclear compartments 2. Problem-Solving: For a series of pre-protein structures, determine their protein orientation, their final localization, location of N and C termini
Unit IV: Signal Transduction	1. Describe signal transduction from a "generic" perspective 2. Describe GPCR (AC or PLC) and RTK (MAPK or PI3K) 3. Describe how the signaling pathways would be affected if there is a mutation in a specific component that is either constitutively activated or non-functional

Table 3.
Summary of Survey Questions and Sample Anonymous Student Responses from Iteration #5

Survey Question	Sample Anonymous Student Responses
How did the following class props/demonstrations alter your understanding of key cell biological concepts and critical thinking skills: a) Protein Translation with student volunteers b) Protein Trafficking/Orientation with Styrofoam Rope Model and Drawings c) Four Signaling Cascades (MAPK, PI3K, GPCR-AC, GPCR-PLC) with the Glitter Board Models and PowerPoint Tools	a) It helps more because we as students get to participate b) Rope model help visualize in 3D so it helps a lot c) Not much helps for me personally They were all very helpful in visualizing the concepts. In particular, the signal cascade models really helped clarify the step-by-step mechanisms involved in these cascade processes. These visual aids helped solidify the information compared to reading it off slides. I enjoyed the props a lot and really appreciated the pictures that were posted to Canvas after class.

create an environment that values each student and individualizes the learning process. This proposed high-quality instruction will accelerate and deepen learning, particularly for those students from URGs and those transferring from community colleges. The cheap and low-tech nature of prop-based approaches make them easily adoptable and scalable to other large enrollment STEM biology courses. Use of this EBT method and teaching culture across multiple key STEM courses will thereby provide greater access to teaching excellence at the university or institutional level in a cost-effective manner.

We hope that our demonstration of using this approach in our own very large-size classrooms will encourage others to engage in similar activities in their classes as well by sharing our methods, resources such as the props, and the assignments we have created. As mentioned previously, broader adoption of these approaches by all sections of our Cell Biology course as well as other cell and molecular biology courses will lead to scaling of these EBTs and make them accessible for a diverse population of students within our STEM pool including URGs and transfer students, thereby helping in reducing the achievement gap in STEM education. In addition, some sections are co-taught by more than one instructor with quite different teaching styles due to logistical reasons. Often students have trouble shifting between teaching styles from one instructor to another

within the semester and this perception can be a deterrent to their continued success in the course. The prop-based approach when adapted in a co-taught course by both instructors would allow students to appreciate the similarity between them and would allow seamless transition from one instructor to the other. Likewise, with suitable modifications, the prop-based approaches can be tailored to online courses as well as to remote classrooms such as during forced periods of remote learning like the COVID pandemic.

Finally, we hope that our review of the refinement, modification, and consolidation of earlier prop-based methods from the literature to encompass a large set of key topics in cell biology sets the stage for serious pedagogy researchers to carry out IRB-approved studies comparing the effectiveness of our integrated approach addressing multiple concepts in the course to the previous approaches, addressing the effectiveness of these approaches for one or a very few concepts only.

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Appendix A
Abbreviations

AC, adenylyl cyclase
AKT, AKT serine/threonine kinase
CAM, Cell and Molecular Biology
DNA, deoxyribonucleic acid
EBTs, evidence-based techniques
ER, endoplasmic reticulum
GPCR, G protein-coupled receptor
IRB, Institutional Review Board
KDEL, lysine-aspartate-glutamate-leucine
KKXX, lysine-lysine-any amino acid-any amino acid
LMS, Learning Management System
MAPK, mitogen-activated protein kinase
MCAT, Medical College Admission Test
Met, methionine
mRNA, messenger ribonucleic acid
PI3K, phosphatidylinositol 3-kinase
PKC, protein kinase C
PKA, protein kinase A
PLC, phospholipase C
RTK, receptor tyrosine kinase
SRP, signal recognition particle
STEM, science, technology, engineering, and mathematics
tRNA, transfer ribonucleic acid
URGs, underrepresented groups