Lights, Camera, Acting Transport! Using role-play to teach membrane transport

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Abstract

Lights, Camera, Acting Transport! is an active and unique role-play exercise designed to teach introductory biology students basic concepts of passive and active membrane transport. The activity involves three acts in which students, representing various molecules, ions and components of the plasma membrane, interact to learn the fundamentals of passive transport, primary active transport and co-transport across cellular membranes. This activity was designed in response to observations that many students struggle to understand the basic principles of membrane transport. After consistently observing high levels of student engagement and enjoyment from this activity, we assessed student learning gains from, and attitudes towards, this exercise. Student understanding of membrane transport significantly improved after participation in the activity, and these improvements were largely retained over time. Moreover, students reported positive attitudes towards the activity in terms of perceived learning and enjoyment, and participation in the exercise significantly increased student confidence. We conclude that this activity constitutes an effective and enjoyable instructional tool that appeals to a diverse population of students.

Learning Goal(s)

At the end of this activity:

- Students will understand how molecules and ions of variable sizes and compositions are transported across a cell's membrane.
- Students will demonstrate the ability to work collaboratively
- Students will demonstrate the ability to communicate their understanding of membrane transport verbally and kinesthetically

Learning Objective(s)

Students will be able to:

- Compare and contrast the mechanisms of simple diffusion, facilitated diffusion, and active transport (both primary and secondary).
- Identify, and provide a rationale for, the mechanism(s) by which various substances cross the plasma membrane.
- Describe the steps involved in the transport of ions by the Na+/K+ pump, and explain the importance of electrogenic pumps to the generation and maintenance of membrane potentials.
- Explain the function of electrochemical gradients as potential energy sources specifically used in secondary active transport.
- Relate each molecule or ion transported by the Na+/glucose cotransporter (SGLT1) to its own concentration or electrochemical gradient, and describe which molecules travel with and against

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Materials and Supplemental Materials: Table 1. Teaching Timeline, Table 2. Student Responses to Open-Ended Questions on Attitudinal Surveys, Table 3. Student Responses to Likert-Type Prompts on Attitudinal Surveys, Figure 1. Classroom Set-up Diagram, Figure 2. Student Learning Gains Measured by Pre-, Post- and Retention Test, Supplemental File S1: Pre-Activity Test with key, Supplemental File S2: Post-Activity Test with key, Supplemental File S3: Think-Pair-Share Prompts with key, Supplemental File S4: Pre-Activity Worksheet with key and Supplemental File S5: Role Cards

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INTRODUCTION

Lights, Camera, Acting Transport! was designed to provide a fun and engaging way for Introductory Biology students to learn the basic terminology and key mechanisms associated with membrane transport. Few introductory biology students at our institution arrive with prior knowledge of this subject matter, beyond a basic understanding of the plasma membrane's structure and function as a semi-permeable barrier. Furthermore, many students find it challenging to accurately visualize, and thereby understand, processes that occur at the molecular and cellular levels (1,2). By creating tangible representations of subcellular processes, this role-play exercise gives students a perceptible framework around which to construct their knowledge of this topic. In addition, the social nature of the activity provides students and instructors with the opportunity to discuss concepts as they are introduced and address questions as they arise. Previous approaches to teaching membrane transport have included the use of computer models, analysis of "classic" papers, and laboratory experiments (3-5) and even a fully scripted play (6). However, we believe that one of the great strengths of the activity described here is its impromptu and interactive nature, which encourages students to actively evaluate and think about the concepts at hand.

Lights, Camera, Acting Transport! has been part of the curriculum of Bio 2: Cells, Molecules and Genes, an introductory-level course for biology majors, at our comprehensive regional university since Fall 2009. The role-play activity involves three acts and is routinely performed with approximately 24 students during a single 110-minute activity (discussion) session. Each act takes approximately 30 minutes, but instructors can choose to implement only one or two of the acts in a single class session if time is limited. The exercise can also be streamlined if the pre- and post-test (Supplemental Files S1 and S2) are not used, the optional Think-Pair-Share activities (Supplemental File S3) are eliminated, and if students prepare in advance through a reading assignment and pre-activity worksheet (Supplemental File S4). Table 1 (on page 4) provides a breakdown of the activities within each act and the estimated amount of time that should be allotted for each.

There were several reasons for selecting role-play as the instructional tool to deliver this material. There is sufficient evidence from the biology education literature to suggest that role-play has been used effectively to teach a number of topics, including protein synthesis (7), glycolysis (8), and optimal foraging theory (9). Several of my own colleagues have used role-play to teach the mechanisms of protein synthesis and food digestion to college students at different academic levels. As a form of experiential learning, the method 1) allows students to immerse themselves in the subject matter, 2) can bring a sense of immediacy and reality to otherwise static academic material, 3) provides a relatively safe environment in which students can practice using and applying new concepts, and 4) represents a change of pace that can be both fun and engaging for students (10, 11). Furthermore, before changing my college major to biochemistry, I spent countless hours studying theatre, dance and music, which gave me the experience and motivation to sit down and write my first play, "Lights, Camera, Acting Transport!"

Although I found the role-play clever and entertaining, I worried that my college students might find it less amusing. To my surprise, I received extremely positive feedback on post-activity surveys and end-of-semester evaluations. Several semesters of enthusiastic reviews and requests for more of these types of activities convinced me of the lesson's effectiveness to engage students, but I wanted evidence that learning was also being achieved. In the Fall 2010 semester, one of my Master's students joined me in teaching, assessing and refining the activity. Over the course of several semesters, we used a pre-test/post-test instrument to examine changes in student understanding, as well as student attitudes on the day of the activity. We gave students the opportunity to provide open-ended feedback on the exercise, and also administered a second post-test ten weeks later to examine student retention of key concepts over time. We are convinced from these data that students not only enjoy the activity, but also learn from it. Furthermore, we have evidence that these learning gains are retained over a 10-week period. In this article, we will focus on the detailed instructions for conducting the activity and will present a summary of select assessment data.

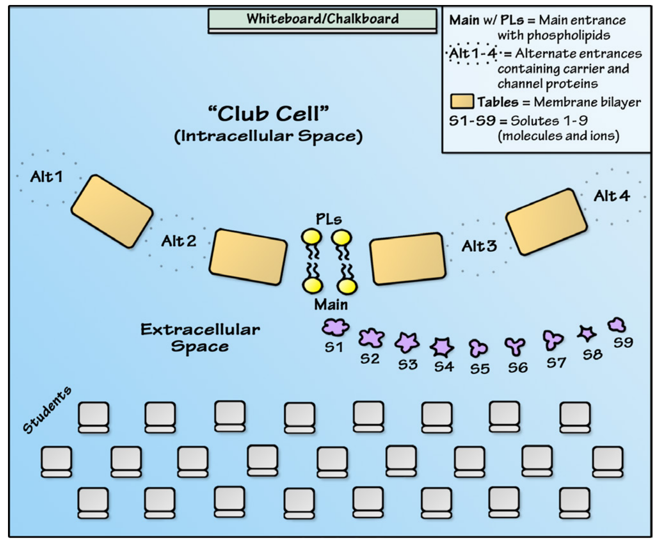

Figure 1. Diagram of classroom set-up for activity.

Materials/Set-up:

- A room with enough space 1) to create a plasma membrane (we use rectangular tables lined up with spaces between them for students playing the roles of membrane components), and 2) for students to move around the set-up (Figure 1).
- A chalkboard or whiteboard to use as needed for stage directions, Think-Pair-Share (T-P-S) prompts, and explanations.
- An overhead projector or large sticky notes (2 ft x 3 ft) to show students T-P-S prompts prepared in advance (optional).
- Role cards (Supplemental File S5) labeled with the names of the molecules that students will be impersonating. Multiple cards will be needed for some terms, so color-coded cards are recommended (e.g., all glucose molecules are printed on yellow paper).
- Index cards for students to use when brainstorming about their subcellular identities.
- Textbooks: Any introductory biology text should cover the material necessary to prepare instructors and students for this activity. We have used both of the following:
    - **Campbell Biology (tenth edition)**. Reece, J.B., Urry, L.A., Cain, M.L., Wasserman, S.A., Minorsky, P.V.,

and Jackson, R.B. San Francisco, CA. Pearson, Benjamin Cummins Publishing. 2013. ISBN-10: 0321775651 and ISBN-13: 978-0321775658.

- **Raven Biology (tenth edition)**. Mason, K. A., Losos, J. B., and Singer, S. R. New York, NY. McGraw-Hill Companies, Inc. 2014. ISBN: 9781259355226.

SCIENTIFIC TEACHING THEMES

Active learning

- Prior to class, students read sections in their textbook covering membrane transport and complete a pre-activity worksheet designed to focus their learning on some key concepts.
- In class, Think-Pair-Share (T-P-S) and role-play are used to actively engage students in the learning process. As the play is essentially unscripted, students must discuss and justify their actions as they attempt to apply their knowledge to the themes of each act.

Assessment

Assessment is ongoing throughout this activity. It is easy to gauge what students know through their actions and verbal responses. Questioning their decisions and evaluating their responses during the activity can provide additional knowledge. Immediate feedback is provided as the instructor plays the role of the director of the play; however, allowing students to discuss and debate prior to providing corrections is advised. In addition, the pre- and post-tests can be administered before and after the activity to assess student learning gains, and the retention test can be administered at some later date to assess retention of concepts. These assessment tools include five multiple-choice knowledge/comprehension-based questions that cover key concepts from the three acts, as well as several Likert-type and open-ended attitudinal questions. The retention test includes the same five multiple-choice questions as the pre- and post-tests, with answers in a different order.

Inclusive teaching

This lesson was designed to appeal to a diverse group of students with a variety of learning preferences. Not surprisingly, it appeals to students who enjoy kinesthetic learning experiences, as they move in and out of "the cell" and simulate the mechanisms of channels and carriers through motion. However, it also appeals to students who appreciate visual learning tools, as it allows them to envision the cellular processes that would otherwise be highly abstract. We have built in time for independent thinking and T-P-S prior to each act, in order to make the lesson less intimidating for the quieter more reflective students. The consistent popularity of this lesson, in addition to our assessment data, suggests that we are appealing to and benefiting all of our learners.

LESSON PLAN

Preparation for Role-Play

We begin the lesson by reviewing the answers to the pre-activity worksheet on a whiteboard. We solicit answers from students and then add detail and explanation, when necessary. This ensures that any misunderstandings from the reading are resolved and provides an opportunity for students to ask questions if they need clarification.

Note: If the pre- and post-tests are used, we collect the pre-activity worksheets as students enter, and hand out the pre-test. We allow students 5-10 minutes to complete the pre-test. After collecting the pre-test, we hand back the pre-activity worksheets. We do not go over the answers to the pre-test immediately, but wait until after the post-test is completed at the end of class.

Next, we provide students with a general description of the activity and the learning objectives. We explain that they will be the actors in a three-act play that will help them understand the various ways that substances pass into and out of the cell, a critical function of the plasma membrane in sustaining homeostasis and life. We describe our role as the director who will make suggestions and prompt students to "consider the motivation" for their actions both during and at the conclusion of each act.

Before each act, we introduce students to the stage setup, pointing out the location of the plasma membrane and the interior and exterior of the cell. We use the whiteboard for sketching out stage directions and prompts as outlined below.

ACT I: The Selective Barrier

Act I takes approximately 35 minutes and addresses the following learning objectives:

- Compare and contrast the mechanisms of simple and facilitated diffusion.
- Identify, and provide a rationale for, the mechanism(s) by which various substances cross the plasma membrane.

The Cast: 4 phospholipids, 1 Na+ ion channel, 1 K+ ion channel, 1 aquaporin, 1 glucose transporter, 1 amino acid transporter; 1 of each of the following: O2, Na+, K+, hydrocarbon, methionine, glucose, H2O, CO2, ATP (18 total).

Note: If the number of students is small, two phospholipids can be used and/or a single, generic ion channel. If there are extra students in the class, you can double up on the substances in line (e.g., two students can represent O2, and argue their case collectively to the bouncers), or pair up students to collectively play a single transport protein. You can also assign extra students to the role of "critics" that remain in the audience, take notes and provide their reviews at the end of the act.

- Introduce Act I. "Club Cell" is an exclusive nightclub in Sacramento, and a variety of molecules (the "public") line up each evening hoping to gain entrance. Four phospholipids (the "bouncers") staff the main entrance and decide if the substances in the line to enter the cell meet the "dress code" to cross the bilayer. The phospholipids must discuss each candidate and agree on a decision, while providing an explanation as to why they let some substances enter and deny entry to others. All substances must begin at this entry point; those that are turned away can either argue their case (if they feel that they were unjustly denied entry) or look for an alternative entrance into Club Cell along the plasma membrane. The alternate entry points are manned by channel and carrier proteins that cater to a different clientele (i.e., larger, charged, and hydrophilic substances). The purpose of this act is to help students understand how solutes (e.g., molecules and ions) of different sizes, shapes and compositions must enter the cell via different mechanisms, even if they are all diffusing

Table 1: Acting Transport-Teaching Timeline

Activity	Description	Time
Pre-Test (optional)	The pre-test consists of five multiple-choice questions related to content to be covered in the activity and two attitudinal questions.	5-10 min
Pre-Activity Review (15 min)	Go over the pre-assignment that students complete before class. This will serve to further prepare students for the activity.	15 min
ACT I (35 min)	• Introduce ACT I and pass out role cards • Students complete Prompt 1 and discuss with partners • Proceed with ACT I role-play • Collect role cards and review ACT I	• 5 min • 5 min • 20 min • 5 min
ACT II (30 min)	• Introduce ACT II and pass out role cards • Students complete Prompt 2 and discuss with partners • Students complete Prompt 3 and discuss with partners (optional) • Proceed with ACT II role-play • Collect role cards and review ACT I	• 5 min • 5 min • 5 min • 10 min • 5 min
ACT III (30 min)	• Introduce ACT III and pass out role cards • Students complete Prompt 4 and discuss with partners • Students complete Prompt 5 and discuss with partners (optional) • Proceed with ACT III role-play • Collect role cards and review ACT I	• 5 min • 5 min • 5 min • 10 min • 5 min
Post-Test (optional)	The post-test consists of five multiple-choice questions related to content covered during the activity and several attitudinal questions.	5-10 min

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across the membrane bilayer.

- Think. Randomly distribute role cards and index cards to students for Act I. Separate the membrane components from the public as you pass out the cards. Ask all students to individually think about their molecular identities and write down important characteristics on their index cards. Students should respond to the following:

Suggested T-P-S Prompt 1

What is your molecular "ID"? For members of the "public," think about size, polarity, and charge. Should you be allowed to enter at the main entrance? If not, what might you need to cross the membrane? For membrane components, think about what substances you will allow to cross and why.

- Pair. Ask students to form small groups (3-4 individuals) to review the questions above and discuss the notes they prepared on their molecular identities. Encourage them to make changes as needed. You may assign the groups such that the molecules wishing to obtain entry ("the public") work together, the phospholipids form a group, and other membrane components work with one another.
- Share. Assign the components of the plasma membrane to their positions. A good first exercise for the class as a whole is to ask the phospholipids how they think they should arrange themselves (i.e., as a bilayer) and why; encourage feedback from all students. Next, line up the public outside of the club. Students are ready to begin with the first substance in line, who should start by introducing him/herself to the phospholipids, and asking for admission into Club Cell. Substances that are rejected by the phospholipids must look for another way in by talking to the other membrane components. Remind students to use their notes to vocally justify all decisions and (if necessary) contestations.
- After all substances are in Club Cell (or have been permanently denied entry), collect the role cards and ask students to return to their seats. Review major concepts on the board, and invite student questions and feedback. If there were critics in the audience, ask them to summarize some of the key points from the act.

Common points of confusion in Act 1:

- Specificity of channels and transporters. If only a generic ion channel is used, students playing the roles of Na+ and K+ will often try to utilize the same channel. This allows for a discussion of specificity of channels. Although methionine is the only amino acid used in Act I (and a generic amino acid transporter is in the membrane), a discussion about specificity of amino acid transporters is also advised.
- Multiple paths exist for certain molecules. Molecules such as water, and even glucose, can pass through the membrane bilayer, but their passage is slow due to polarity and size. Aquaporins are available in cells to facilitate rapid transport of water, and many different transporters promote the uptake of glucose.
- Concentration gradients drive diffusion. While O2 and CO2 are both part of the "public" attempting to get into the cell, a discussion about the directions that these molecules are typically traveling is useful. If prompted to think about cellular respiration, students usually figure out that the cell is taking up more O2 and releasing more CO2. This can lead to a discussion about the role of concentration gradients in simple and facilitated diffusion. Single molecules can enter or exit, but the net movement depends on the concentration of the molecule on both sides of the membrane. This is an important point to raise, since this act involves only single molecules on the outside of the cell.
- The location of ATP. There is one molecule of ATP in line and students are generally confused about how to get it across the membrane. This allows for a review of the structure of ATP (students forget how large and charged it is) and a discussion about the role of ATP in the cell. While ATP is found in extracellular spaces, it is produced and utilized inside the cell. It cannot enter using any of the mechanisms available in this act.

ACT II: Pump It Up! (The Concentration Gradient)

Act II takes approximately 30 minutes and addresses the following learning objectives:

- Describe the steps involved in the transport of ions by the Na+/K+ pump
- Explain the importance of electrogenic pumps to the generation and maintenance of membrane potentials.
- The Cast: 8 Na+ ions, 8 K+ ions, 2 students as the Na+/K+ pump, 1 adenosine, 3 phosphates, 1 Na+ channel, 1 K+ channel (24 total).

Note: If the number of students is limited, students can carry multiple Na+ or K+ ion cards; alternately, the two ion channels can also play the Na+/K+ pump, as these roles can be temporally separated. The adenosine and phosphates work together as a single ATP molecule; alternately, one person can play ATP, but should still carry separate cards or balloons to represent three separate phosphate groups. If there are extra students, students can partner up to play a single role or assume the role of critics.

- Introduce Act II. "Club Cell" is anything but a passive environment. Energy, in the form of ATP and in the membrane potentials, is required to keep the establishment functioning. The purpose of this act is to introduce the concept of a membrane potential (form and function), and to illustrate how a cell uses primary active transport and ATP to establish and maintain its membrane potential.
- Think. Pass out a new set of index cards. On the board, write up a preliminary cast of 8 Na+ ions and 8 K+ ions, and sketch a simple membrane (with no proteins). Label the inside and outside of the cell. Point out to students that the membrane currently has no transport proteins, and ask students how they would distribute the current cast of ions to mimic the membrane potential of a real cell. Provide students with the following prompts:

Suggested T-P-S Prompt 2

What is a membrane potential and why is it important? Is the inside of the cell positive, neutral, or negative in relation to the outside? Is the concentration of Na+ inside of the cell higher than, equal to, or lower than outside of the cell? Is the concentration of K+ inside of the cell higher than, equal to, or lower than outside of the cell? How will you distribute the Na+ and K+ ions to mimic a real membrane potential?

- Pair. Have students work in small groups of 3-4 to answer the questions above and agree on the starting positions of the cast.

- Share. Have students help with the set up for this activity by asking them how they would arrange the ions across the membrane and why. Sketch the membrane and ion distribution according to student suggestions. At this point, move ions (on the board) into the following arrangement as needed: 7 Na+ and 2 K+ ions outside of the cell; 1 Na+ and 6 K+ ions inside of the cell. Note that there is more than one possible arrangement of the ions that will yield correct answers to the questions of the T-P-S Prompt. If the class arrives at one of these alternate correct answers, you can either leave it or change it, at your discretion. It will not adversely affect the play, since the act actually begins with ions moving out of these starting positions, flowing "downhill" through the ion channels until concentrations become balanced on both sides. Explain that this arrangement represents an approximation of the normal membrane potential of the cell, and discuss any points of confusion. In addition, be sure that you have discussed the answers to the Think-Pair-Share questions above.
- Ask students if any movement of ions can occur across this membrane. They may recognize that there is a steep electrochemical gradient across the membrane for both Na+ and K+, but should also recognize that the ions cannot move across the phospholipid barrier. Therefore, no movement can occur.
- Think/Pair. Add the rest of the cast members to the list on the board, and pass out the role cards. Ask students to respond to the following prompts. Students can work independently, or discuss with a partner if they wish.

Suggested T-P-S Prompt 3

If you are an ion, consider whether you are "inclined" to cross the membrane under current conditions. Why or why not? Based on the new cast members, what might you require to move? If you are one of the new cast members, consider who you are and what you do. Where should you be located? How might you interact with the other members of the cast?

- Share. Ask the ions to arrange themselves on stage according to the stage directions on the board, and introduce the ion channels to the membrane. Once everyone is in place, Na+ and K+ should move down their concentration gradients until the ion concentrations are balanced. Encourage students playing all of the roles to discuss their movements.
- Ask students if they think there is a problem for a living cell with the current ion distribution. They should notice that the membrane potential has been disrupted and must be restored. Ask students how the cell will accomplish this (i.e., with a Na+/K+ pump and ATP to power it).
- Ask the final cast members (Na+/K+ pump and ATP) to find their places on stage. Have the Na+/K+ pump go through one round of pumping ions (go through each step, including the cycling of ATP to ADP in which one phosphate group needs to be donated to, and later released from, the pump). This will restore the electrochemical gradient and negative cell interior.
- The whole process can be repeated if students need reiteration. It goes much more quickly in subsequent rounds.
- After Act II, collect role cards and have students return to their seats. Review major concepts and invite student questions and feedback. If there were critics in the audience, ask them to summarize some of the key points from the act.

Common points of confusion in Act II:

- The sequence of events presents the primary challenge for students in this act. In particular, students struggle with the role of ATP hydrolysis and the timing of phosphorylation and dephosphorylation to drive the process.
- The fact that the pump is not a channel, but rather a transport protein that binds to the ions and assists their passage across the membrane. This is instigated by the conformational changes resulting from phosphorylation and dephosphorylation.
- Students may fail to recognize the connection between the difference in the number of Na+ and K+ ions that are transported to the separation in charge across the membrane.
- If multiple rounds of the process are run, students often fail to consider the electrochemical gradients of the ions.

ACT III: Gatorade®: Is It in You?

Act III takes approximately 30 minutes and addresses the following learning objectives:

- Explain the function of electrochemical gradients as potential energy sources specifically used in secondary active transport.
- Relate each molecule or ion transported by the Na+/glucose cotransporter (SGLT1) to its own concentration or electrochemical gradient, and describe which molecules travel with and against these gradients.

The Cast: 9 glucose molecules, 8 Na+ ions, 2 students as the Na+/glucose cotransporter (19 total).

Note: As in the previous two acts, students can double up in roles (if too few) or play the role of critics (if more students than roles exist).

- Introduce Act III. To continue the analogy of Club Cell, describe the following scenario. After dancing for hours in the hot dance club, you find yourself depleted of fluids and energy. This is nothing a nice cold Gatorade® can't cure! The purpose of this act is to show how cotransporters function, using the example of the Na+/glucose cotransporter (SGLT1) that is essential for the uptake of glucose in the lumen of the intestine.
- Think. Pass out index cards, and write the full cast list on the board. Draw the basic membrane (i.e., no proteins in it yet) on the board, and label the inside and outside of the cell. Add the following information for glucose: there is approximately 145 mM outside of the cell, and a concentration of 150 mM inside. The body wants to get glucose into the cell, but there is a problem–glucose would have to move up its concentration gradient, and there is no ATP in sight. Let students respond to the following prompt and determine how to distribute the rest of the cast of molecules:

Suggested T-P-S Prompt 4

Is co-transport active or passive? What force drives the movement of molecules in co-transport? Using the template *on the board as a starting point, sketch the starting positions of all cast members.*

- Pair. Have students work in small groups of 3-4 to discuss the prompt above and agree upon starting positions for the cast.
- Share. Ask students to help with the set up for this act, as they did in Act II, by asking them how they would arrange the ions across the membrane and why. Sketch the membrane and ion distribution according to student suggestions. Make any adjustments needed on the board so that there are 4 glucose molecules and 8 Na+ ions in line for Club Cell ("outside," in the lumen of the intestine), with 5 glucose molecules and no Na+ ions inside Club Cell. The gradient is exaggerated for the purposes of the activity; you may want to point out that in a real cell, there would still be some Na+ inside, just less than outside.
- The Na+/glucose cotransporter is situated in the membrane of this intestinal cell. Provide students with a quick diagram of an intestinal cell and discuss the answers to the T-P-S questions above. Be sure to reiterate that there is no ATP in the cast for this act, and ask students to explain why this is so.
- Think. Pass out index cards and role cards, and ask students to respond to the following:

Suggested T-P-S Prompt 5

What role will your character play? How will electrochemical and concentration gradients influence your actions and the movement of other characters? Who gets to move and why? How do you think a Na+/glucose cotransporter might work?

- Pair. Ask students to find a partner (or two) with the same identity with whom to discuss their character and answer the above questions. While students playing the roles of glucose and Na+ discuss the T-P-S prompts, the instructor can spend some time with the cotransporter pair and, as needed, guide their understanding of cotransporter function: this cotransporter will only let Na+ and glucose in together, in a 2:1 ratio (2 Na+ ions bring in 1 glucose), and only while the concentration gradient for Na+ exists.
- Share. Ask the students to arrange themselves according to the stage directions on the board. As in Act I, the way into Club Cell is through the main entrance, which is now manned by a specific cotransporter. As students in line approach the cotransporter, they must try to justify their entry into Club Cell, and the cotransporter has to justify who gets in and what criteria must be met. In addition, the line outside will get shorter only as long as there is an electrochemical gradient to "pay" the price of admission.
- Once the action has stopped (i.e., students have figured out how to use the cotransporter and the Na+ gradient is gone–two cycles), reiterate to everyone that it is ions moving with their electrochemical gradients that power co-transport; only glucose is moving against a gradient. Ask students to explain how the cell would re-establish the electrochemical gradient to power the continued use of this cotransporter (i.e., Na+/K+ pumps).
- Collect the role cards and have students return to their seats. Review key concepts and answer any final questions. If there were critics in the audience, ask them to summarize some of the key points from the act.

Common points of confusion in Act III:

- The multi-faceted role of the plasma membrane. Act III involves only the SGLT1 Na+/glucose cotransporter; however, it is important for students to understand that all of the activities covered in all three acts are working simultaneously to accommodate the dynamic needs of the cell. For instance, in Act III, there would also be aquaporins in the membrane allowing water to enter the cell along its own concentration gradient, and O2 and CO2 would be flowing across the membrane in response to concentration changes that result from cellular respiration.
- Symport and antiport. While the SGLT1 transporter is a symporter, transporting the two different molecules in the same direction, some cotransporters assist with the passage of molecules in opposite directions. The same necessity of an electrochemical gradient applies for both mechanisms.
- Movement by different mechanisms. After Act III, students have observed the transport of Na+ by three different mechanisms (a channel, an electrogenic pump and a cotransporter) and the transport of glucose by at least two–a facilitated transporter and cotransporter (three if you consider that it can pass slowly through the lipid bilayer). A review of the similarities and differences of these mechanisms, with a discussion of when and why the cell requires multiple processes to transport the same molecules is a nice way to summarize the act and entire role-play activity.

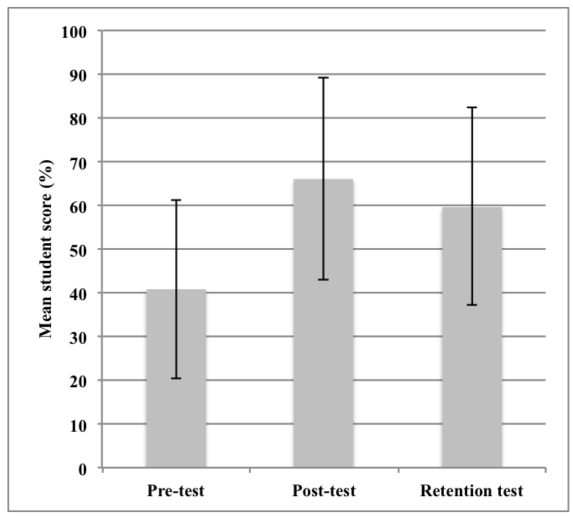

Figure 2. Student Learning Gains Measured by Pre-, Post- and Retention Test Student scores (mean ± SD) from the pre- (40.8 ± 20.5%), post- (66.1 ± 23.2%), and retention (59.6 ± 22.6%) tests for the Fall 2011 and Spring 2012 semesters (N = 174). All differences between pairs of scores (pre-post, pre-retention, post-retention) are significant ($p < 0.001$; □ = 0.017).

TEACHING DISCUSSION

Results from our evaluation indicated that student understanding of membrane transport consistently improved after participation in the role-play activity, and after ten weeks, these learning gains were largely retained (Figure 2).

These differences among test scores were significant (Friedman test: □ 2(2) = 152, $p < 0.001$; □ = 0.05); moreover, these differences were significant between each pair of scores (post-hoc Wilcoxon signed-rank tests: pre-post, $Z = -9.87$, $p < 0.001$; pre-retention, $Z = -7.91$, $p < 0.001$; post-retention,

$Z = -4.17$, $p < 0.001$; □ = 0.017). Membrane transport was not formally reviewed in the nine weeks between the lecture exam covering this material and the retention test, and given that students were not informed in advance of this test, it seems plausible that the observed retention was due, at least in part, to participation in this role-play activity. Although the learning gains and knowledge retention observed in this study were highly significant, it is worth noting that there was considerable variation among student scores. This raises several interesting questions for future research. For example, do demographics influence student performance? Are there specific content areas with which students struggle?

As a complement to the positive learning outcomes, student attitudes towards the exercise were also quite positive. Students believed that they were learning, and they enjoyed themselves in the process. Open-coding qualitative analysis of the two free-response questions on the post-test led to the identification of several categories of student responses (Table 2 on page 10). The most common reasons cited for enjoying the activity related to the inherent nature of this role-play, with its interactive, kinesthetic and collaborative characteristics. This activity provided a clear change of pace from conventional lecture-based curricula, and students recognized and valued these differences. Students further appreciated that the activity provided a way for them to visualize the molecular mechanisms and discuss their movements in an open forum. For example, one student commented that he/she benefited from the way the class "discussed possible explanations for the activities of different substances as they try to cross the membrane." A few students reported feeling uncomfortable with being "put on the spot," or felt unprepared for the activity, and quite a few contributed ideas for improvements, such as changing the pace of the acts and adding additional instructor or visual aids.

Data from the Likert-type questions in the Fall 2011 and Spring 2012 cohorts showed that students enjoyed the activity and believed they were learning, and that their confidence improved after participation in this activity (Table 3 on page 10). This improvement in confidence from pre- to post-test was highly significant (Wilcoxon signed-rank test, □ = 0.05: Pre-Post, $Z = -5.796$, $p < 0.001$). Increased confidence may be important insofar as confidence can be considered a proxy for the closely related construct of self-efficacy (12). Self-efficacy is a specific measure of an individual's belief in his or her own ability to carry out a given task (13), and has been linked to higher academic performance in a number of studies (14). While many factors are involved in academic achievement, self-efficacy may play an indirect role because it leads to increased effort and persistence; students who believe that they can succeed will try harder and longer than those who do not, which can result in greater success (14). It is our hope that the use of nontraditional instructional strategies, like the one describe in this article, will generate an engaged and confident student body, leading to the retention and success of a more diverse population of students in the sciences.

SUPPLEMENTAL MATERIALS

- Supplemental File S1: Pre-Activity Test with key
- Supplemental File S2: Post-Activity Test with key
- Supplemental File S3: Think-Pair-Share Prompts with key
- Supplemental File S4: Pre-Activity Worksheet with key
- Supplemental File S5: Role Cards

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Table 2: Acting Transport-Student responses to open-ended questions on attitudinal surveys

Open-Ended Question	Response Category	Reason for Response	% of Respondents
What did you like best about the activity?	Activity was enjoyable	Interaction with the content	16.7
		Hands-on (physical) nature	12.6
		Collaboration with peers	8.6
	Activity facilitated learning	Through visualization	27.0
		Through verbal explanation	6.3
		Through physical interpretation	4.0
		By applying content	2.9
What did you like least about the activity?	Aspects students disliked	Lack of participation by some	4.0
		Made them uncomfortable	3.4
		Felt unprepared for activity	2.3
	Aspects that could be improved	Pacing (too fast or too slow at times)	7.5
		More instructor support	2.9
		More visuals or props	1.1

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Table 3: Acting Transport-Student responses to Likert-type prompts on attitudinal surveys*

Attitude Evaluated	Survey	N	% Positive	% Negative
Beliefs about understanding ¥	Post-test	169	99.41	0.59
Beliefs about retention ¥	Post-test	165	98.79	1.21
Enjoyment #	Post-test	75	96.00	4.00
Confidence #	Pre-test	73	68.49	31.51
	Post-test °	73	94.52	5.48

* Results include only those surveys where students selected positive (“Agree” and “Agree Somewhat”) or negative (“Disagree” and “Disagree Somewhat”) responses. Surveys with “Undecided” responses (Fall 2011 only, ≤ 5% of all surveys) or missing data (≤ 1% of all surveys) were excluded from the analysis of the corresponding prompt. † Data from Fall 2011 and Spring 2012 semesters.

¥ Data from Fall 2011 and Spring 2012 semesters.

Data from Spring 2012 semester.

° The change in confidence from pre- to post-test is significant at $p < 0.001$.

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