Housemates analogy for membrane potential

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Abstract

University-level physiology courses are considered challenging. Postsecondary instructors indicate the top three reasons that make physiology courses difficult for student are 1) the need for the learner to reason mechanistically, 2) the belief among students that memorization is equal to learning, and 3) the need to think about the physiological systems as dynamic systems. One topic that encompasses all three aforementioned challenges is membrane potential and its determinants in living organisms. Membrane potential is the mechanism that underlies numerous physiological processes; memorization of these processes does not equate to understanding, and its very nature is highly dynamic. Unfortunately, students find the topic challenging, and even students who have learned and practiced the topic in previous terms, fail to retain the conceptual understanding of the underlying mechanisms. Importantly, understanding many systemic physiological processes relies on students’ mastery of concepts related to membrane potential. Stephan H. Wright rightfully wrote that “It would be difficult to exaggerate the physiological significance of [membrane potential]”. Therefore, to more effectively facilitate students’ learning of additional topics, educators must ensure that students can build on, understand, and appreciate the complexities of membrane potential determination. This article presents a tool to aid instructors of all level in teaching the topic of membrane potential.

analogy; membrane potential; physiology education

INTRODUCTION

University-level physiology courses are considered challenging (1). Postsecondary instructors indicate that the top three reasons that make physiology courses difficult for student are 1) the need for the learner to reason mechanistically, 2) the belief among students that memorization is equal to learning, and 3) the need to think about physiological systems as dynamic systems (1). One topic that encompasses all three aforementioned challenges is membrane potential and its determinants in living organisms (2, 3). Membrane potential is the mechanism that underlies numerous physiological processes, and memorization of these processes does not equate to understanding, and it is a highly dynamic process. Unfortunately, most college students find the topic challenging, and even students who learned and practiced the topic in previous terms fail to retain the conceptual understanding of the underlying mechanisms (2). Importantly, understanding many systemic physiological processes relies on students’ mastery of concepts related to membrane potential (4). Stephan H. Wright rightfully wrote that “it would be difficult to exaggerate the physiological significance of [membrane potential]” (4). Therefore, to more effectively facilitate students’ learning of additional topics, educators must ensure that students can build on, understand, and appreciate the complexities of membrane potential determination.

The ability to build on an understanding of concepts (like membrane potential) to better learn other, more complex, topics in the future is termed “scaffolding” in educational pedagogy. Scaffolding can be roughly defined as instructional and structural support that aids students to achieve and function at their highest cognitive capacity (5). Scaffolding is a well-established and valuable approach to create self-regulated learners (5), improve learning outcomes, and cultivate critical thinking skills (5–7). In my experience, a strong understanding of membrane potential is crucial for learning and mastering the concepts of cell excitability, transmission of information throughout the nervous system, muscle contraction, cardiac function, and a host of other topics. Unfortunately, on the basis of impressions from peer educators, as well as my personal experience, the concept of membrane potential is challenging for many students to master (2, 4). To aid with student mastery of this important concept, I have developed an analogy that is modifiable, familiar, and representative. Familiarity and representativeness are suggested as criteria for effective analogies (8). I used the analogy presented here in a large (~400 students) introduction to physiology lecture course and on a separate term in supplementary discussion sections for the same course (up to 30 students). In the large classroom, I used the analogy following a traditional explanation of membrane potential. In the smaller discussion sections, I used the analogy as an activity that included input from students (think, pair, share), class discussion, and questions that students answered in groups. In my experience, the analogy is more effective when presented verbally in addition to text.
handouts. Verbal presentation encourages class discussion and allow for clarifications if needed.

In simple terms, membrane potential \( V_m \) could be described as follows: \( V_m \) is the potential electrochemical energy across a membrane that is determined by the forces (both electrical and chemical) that act on ions across the cell membrane. \( V_m \) for a specific membrane may be estimated by considering the ions to which a membrane is permeable and the ions’ equilibrium potential \( E_{ion} \) (also known as the reversal potential or the Nernst potential). An ion’s \( E_{ion} \) is a unique \( V_m \) at which the specific ion “experiences” no net movement across the membrane because the electrical and chemical forces that act on the ion are equal and opposite to one another. At any other \( V_m \), the two forces that act on the ion are not at equilibrium and the ion will move across the membrane in a specific direction until this ion’s \( E_{ion} \) is reached (assuming the membrane is permeable to the ion).

Because \( E_{ion} \) for most ions are different, \( V_m \) is determined by considering the \( E_{ion} \) of all the ions to which the membrane is permeable. However, \( V_m \) is not determined by equally integrating the \( E_{ion} \) of all permeable ions. Instead, each ion’s \( E_{ion} \) is weighted based on the ion’s membrane permeability \( P_{ion} \). \( V_m \) and its determination are beautifully captured by the Goldman-Hodgkin-Katz flux (GHK) equation (Fig. 1A) (9). The author realizes that this explanation is very simplified. However, this level of understanding is usually required of most college-level students and is a good starting point for deeper understanding. Unfortunately, this topic is not intuitive for many students, and some students do not feel comfortable with mathematical explanations, such as the GHK equation for physiological concepts (an issue that alone could be a topic for a few research programs). In my experience, there is a need for a simple and effective method for communicating the concept of \( V_m \) to help the increasingly diverse student population to master the concept with greater ease; this is true with both undergraduate and postsecondary students. Failing to master this topic ensures a weak connection to the physiological concepts of membrane potential. In this analogy, I asked students to reflect on their personal experiences, which makes the analogy relatable and relevant to virtually all students. Underlined items below are modifiable and could be determined by the students or the instructor. Students could be paired and asked to input their personal information into the analogy.

**GENERAL DESCRIPTION OF THE ANALOGY**

The analogy begins with descriptions of two housemates. The first is named Nancy (she/hers). Nancy moved to your institution from the Lut Desert in Iran. The second student is named Khalid (he/his). Khalid moved to your institution from Fargo, ND. To engage the student, the instructor can ask students to create a background story and add additional details

![Figure 1. Simplified Goldman-Hodgkin-Katz (GHK) flux equation (A) and the Agreement of Room Temperature (ART) equation (B). Similar shapes around terms in either equation reflect connected terms.](http://advan.physiology.org)
about each housemate. Nancy and Khalid moved together into a house that has temperature control in each of the bedrooms. Nancy, who is used to the warm weather, decides to set the thermostat in her bedroom to 85°F, and Khalid, who is used to the cold weather, sets the thermostat in his bedroom to 65°F. At first, Khalid stays in his room and Nancy stays in her room. The two housemates do not interact much because the joint living area does not have a system to control the temperature. After complaining, their landlord agrees to install a new system in the joint living area. The two housemates are excited, but after the system is installed, they have a difficult time deciding what should be the set temperature at the joint living area. As the housemates pay equal parts of the rent, Nancy and Khalid decide to set the temperature right in the middle of their personal preferences at 75°F (Fig. 2A).

A couple months pass by, and Nancy loses her job. Khalid, being a very generous housemate, offers to pay three-quarters of the rent. However, because Nancy is paying a smaller portion of the rent, Khalid asks to set the joint living area temperature closer to his preferred temperature of 65°F. Nancy agrees, and on the basis of the relative portions of the rent each housemate pays the two decide to set the joint living area temperature at 70°F (Fig. 2B). The following month, Nancy still has no job. Khalid, who really enjoys Nancy’s company, offers to pay 90% of the rent. Again, because of Khalid’s growing portion of the monthly rental payment, the housemates decide to set the temperature in the living area at 67°F (Fig. 2C). Another month passes by, and Nancy wins the state lottery. She asks to pay 95% of the rent to thank Khalid for his kindness. Because Nancy pays a much larger portion of the rent, the shared area temperature is now set at 84°F (Fig. 2D). The following month, Nancy finds a new job, and everything goes back to normal with the temperature in the shared space being set at 75°F (Fig. 2A).

In this analogy, each housemate represents an ion. The housemates’ preferred temperatures represent the ions’ $E_{ion}$.

The temperature at the shared living-area represents $V_m$. Lastly, the proportion of the rent paid by each housemate represents $P_{ion}$ for each ion. The dynamic relationship described in this analogy is intuitive to students. Another benefit of this analogy is that it also can be mathematically explained with an equation that is similar to the GHK equation. As an alternative for the GHK equation, I termed the Agreement of Room Temperature (ART) equation (Fig. 1B).

Using the ART equation, changes that are described in the analogy can be used to create fluctuations across a time axis.

Figure 2. The roommate analogy for membrane potential (see text for details and context). A: rent is equally divided between the roommates and the temperature in the shared living area is right in the middle of the roommates preferred temperature. B: Khalid is paying three-quarters of the rent, bringing the shared area temperature closer to his preferred temperature. C: Khalid is paying 90% of the rent, bringing the shared area temperature closer to their preferred temperature. D: Nancy is paying 95% the monthly rent, bringing the shared area temperature closer to her preferred temperature.

Figure 3. Graph for changes in room temperature based on the analogy. This kind of graph can be given to student already completed or blank; if blank, students can be asked to complete it using the Agreement of Room Temperature (ART) equation. Points 1 and 5 represent Fig. 2A. Points 2, 3, and 4 represent panels 2, 3, and 4, respectively, in Fig. 2.
similarly to changes in membrane potential that are seen in real life (e.g., action potential and graded potential) (Fig. 3).

CONCLUSIONS, LIMITATIONS, AND USE

The presented analogy aims to help students in physiology courses understand how $V_m$ is determined. The analogy is intuitive and versatile and allows the instructor to easily modify details in order to emphasize specific subtopics. Examples of possible modifications include adding/removing housemates, changing the housemates’ temperature preferences, and changing the proportion of rent paid by each housemate. The analogy could be used as part of a homework assignment that precedes an in-class membrane potential unit. Alternatively, it could be presented in class as a “story” and followed by practice questions. Practice questions may include the following: “based on the scenario, what would you expect the shared room temperature be if Nancy paid 100% of the rent? On the other hand, if Khalid were wearing a heavy coat and changes their preferred temperature to 55°F, what would be the temperature in the shared room? The change in personal preferred temperature represents changes to an ion’s $E_{i\text{on}}$ (based on concentration changes for example). Lastly, revealing the connections between the analogy and $V_m$ could be done by either the instructor or the students. I found that the different approaches for revealing the connections work differently for different students. Therefore, in my small discussion sessions, I start by asking the students to postulate about the connection to the physiological concept of membrane potential before revealing the connection on my own.

Lastly, a point of confusion sometimes arises when students think of the rooms as the two sides of the membrane or the two forces that act on the ion. A question about the relevancy of three rooms in the analogy may come up. Thus, for a successful use of the analogy, it is imperative that the instructor mentions and emphasizes the fact that each bedroom’s temperature represent a specific ion’s $E_{i\text{on}}$ and that the shared living area represents the cell’s $V_m$. The emphasis is important to ensure that students understand that each ion’s $E_{i\text{on}}$ is dependent only on the ion charge in relation to the cell $V_m$ and the ion concentrations across the membrane. As mentioned earlier, the instructor should make sure that students know how to estimate $E_{i\text{on}}$ before using this analogy. I emphasized this point in the analogy by stating that in each of the bedrooms the housemate can decide what the temperature will be and what to hang on the walls with no consideration of the other housemate. The bedroom temperature preference is personal to each housemate, just like an $E_{i\text{on}}$ is specific for an ion. Another limitation of this analogy is that it does not explain the required preceding concepts that allow us to determine $E_{i\text{on}}$. The analogy does not cover the forces on both sides of the membrane or the concentrations of individual ions across the membrane. Concentration differences must be discussed before the use of the analogy and weaved into the discussion that should follow the analogy’s use. Luckily, I found that students usually can grasp how the chemical force and electrical force act on the ion independently. Many times, I use vectors to describe the added effect of the two forces. Additionally, I use a scenario in which opposing advice from two friends (representing each of the forces) is given to me. My decision on how to act is then based on how strong the influence of each friend on me is. If I weigh the advice of both friends equally, their influence is canceled out, which represents $E_{i\text{on}}$. In conclusion, on the basis of my experience, the analogy I shared here is valuable to students’ learning and understanding of membrane potential determination. I look forward to receiving future feedback. I hope to be hearing ideas for further expansion of this analogy that will make it more inclusive and complete.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

A.D. conceived and designed research; A.D. prepared figures; A.D. edited and revised manuscript; A.D. approved final version of manuscript.

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