Quantitative Modeling of Membrane Transport and Anisogamy by Small Groups Within a Large-Enrollment Organismal Biology Course

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INTRODUCTION

The third semester of the introductory biology sequence at our institution is Organismal Biology. It introduces the physical and chemical constraints common to all life and explores their implications for the structure, function, and evolution of multicellular organisms. An additional goal, shared by many biology faculty members (3), is to use quantitative modeling to develop intuition and generate testable hypotheses about biological processes. The course shares content with traditional anatomy and physiology courses but is distinguished by its emphasis on principles and evolution and by minimal memorization of anatomical structures. The lack of a laboratory component challenges instructors to use classroom time in innovative ways.

We recently developed and assessed group active engagement (GAE) exercises for our Organismal Biology class (2). GAE activities use different modeling approaches to explore biological ideas, and they were designed to be implemented in a traditional lecture hall setting. Here we present two such activities that use spreadsheets (Appendices 1 and 3) and simple quantitative models to provide insight into phenomena related to reproduction (anisogamy) and digestion (membrane transport). Modeling exercises related to neuron physiology and biomechanics are presented elsewhere in this volume (1).

PROCEDURE

Prior to the GAE class session, students are asked to examine a set of PowerPoint slides (available through the course website) that present important background that motivates the GAE activity (Appendices 2 and 4). Students then take an online, untimed quiz to test their understanding (and ensure preparation) before class (Appendices 2 and 4).

Students are urged to access the Excel spreadsheets via the course website (Appendices 1 and 3) or cloud-based Google Sheets before the class meeting.

At the beginning of GAE class meetings, students are given a printed worksheet and instructions. They open the spreadsheet on at least one computer per group of four students. Groups then input and graph data, extract information, and synthesize their results. Student facilitators assigned to different parts of the room encourage each group to verbalize their thinking about the activity. For a class of 125 students, we had five such facilitators (three graduates, two undergraduates). Three to four times during the 50-minute class period, the instructor brings the class together to build consensus about the findings, catch up any student stragglers, and set up the next part of the exercise. Below we briefly describe two GAE exercises we employed in 2014 and 2015.

GAE exercise 1: The evolution of anisogamy

In our discussion of sexual reproduction and development, we note the convergent evolution of anisogamy (the existence of small and large gamete types) in several multicellular lineages (e.g., land plants, metazoans). This exercise develops a simple model to demonstrate how the simultaneous requirements of a relatively large zygote and the need to unite gametes at a distance (Appendix 2, p. 7–10) jointly select for sexual specialization. Key assumptions are that 1) there is a constant amount of material available for the production of gametes (Appendix 1, “size vs. number” sheet), 2) zygote viability is hypersensitive to reductions in size (i.e., the relationship between gamete size and viability is non-linear and parabolic), and 3) the probability of successful unification of gametes is a linear, negative function of gamete volume (e.g., a gamete of volume N mm\textsuperscript{3} will have twice the chance of finding a mate as one of 2N mm\textsuperscript{3}). When isogamy is enforced, gametes are selected to be of intermediate size, a compromise (Appendix 1, “isogamy” sheet). When specialization is allowed, however, both sperm-makers (males) and egg-makers (females) enjoy increased reproductive success (Appendix 1, “viability specialist” and “motility specialist” sheets). This benefit would also exist for simultaneous hermaphrodites that outcross.
Tip 1. Students may notice that the model will not predict a fitness advantage for large eggs if the relationship between viability and mass is linear rather than exponential. If the class meets for longer than 50 minutes, this point could be made explicitly by adding an additional column and plot to the spreadsheet. Because anisogamy is nevertheless common, it suggests that embryos are indeed hypersensitive to reductions in size. However, not all multicellular eukaryotes produce complex embryos from their zygotes. For example, fungi have neither embryos nor motile gametes. Importantly here, neither are they anisogamous.

Tip 2. The take-home lesson—that under certain conditions specialization into male and female benefits both sexes relative to isogamy—is summarized by the table at the end of the worksheet (Appendix 2, p. 5). Reducing the results this way greatly reinforces the main point. However, we also emphasize to students that the validity of this conclusion is dependent upon the initial assumptions.

GAE exercise 2: Membrane transport

In the context of digestion and nutrient uptake, we discuss the two basic different routes solutes (nutrients) can take into a cell: direct diffusion through the plasma membrane vs. passage through a protein channel or transporter. The problem of how to distinguish between these two broad classes experimentally is posed and discussed (Appendix 4, p. 5). Students use a free online transport simulator (http://phet.colorado.edu/en/simulation/membrane-channels) to produce virtual data relating import rate and solute concentrations. Each group produces one replicate of the simulation, and the cloud-based spreadsheet is set up to automatically pool and graph the full class's dataset as they are added in real time. In doing so, the students demonstrate the saturable nature of transporters. Data provided in the Appendix 3 spreadsheet file were produced by students in 2015.

Tip 1. Running the simulator on student-provided laptops has worked in two consecutive years. However, it was common to have only one serviceable unit per group. Testing the simulator on a range of machines enables anticipation of issues some students will face. A good alternative is to meet in a computer lab with a standard operating system and browser.

Tip 2. Working with the collective population of the cloud-based spreadsheet data in real time requires at least one networked computer per group. At times our classroom’s wireless network struggled to handle this load.

CONCLUSION

With appropriate student preparation and attention to the technology required to implement them, the GAE exercises described here are a stimulating alternative to lecture. Even with the necessary preliminaries in place, however, students spend considerable effort understanding the mechanics of spreadsheet applications. Though this effort might ideally be spent on understanding the science, we believe that the ubiquity of Excel in the “real world” justifies these struggles.

SUPPLEMENTAL MATERIALS

Appendix 1: Anisogamy exercise spreadsheet
Appendix 2: Anisogamy worksheet, preparatory materials, and pre-activity quiz
Appendix 3: Membrane transport simulator data (2015, University of Maryland)
Appendix 4: Membrane transport worksheet, preparatory materials, and pre-activity quiz

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