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ILLUMINATIONS

The Fictional Animal Project: a Tool for Helping Students Integrate Body Systems

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WHEN TEACHING PHYSIOLOGY, faculty members typically guide students in learning the body systems one at a time: examining the organs and tissues, overall functions, and how processes are carried out at a cellular level. We then move on to another body system, then another, etc. While this is a logical and practical teaching approach, what often gets left behind is an exploration of how systems are integrated. As instructors, we may not readily prompt or require students to think about systems integration for a host of reasons. As instructors of physiology, the only time, if at all, we may prompt students to think about system integration is on exams, even if they have not had exposure to this way of thinking before.

The integration of systems is a fundamental principle in physiology (called "interdependence" in Ref. 2). This study showed that faculty members found interdependence to be the 4th most important concept in physiology out of 15 areas identified by faculty. Interdependence is represented as "Cells, tissues, organs, and organ systems interact with one another (are dependent on the function of one another) to sustain life" (2). Without understanding the way that systems affect each other, one cannot truly understand the function of any system alone, the overall condition of an organism, or the interactions between an organism and its environment.

Students often need extensive guidance in understanding systems integration. Physiology faculty members have reported that "students fail to appreciate the integrative nature of physiological mechanisms" as the sixth highest reason (of 17 reasons total) that they believe makes physiology hard to learn (1). To help students understand how body systems affect each other in the context of organism-level function as well as the diversity of animal system designs, we asked students to create a fictional animal based on combinations of particular systems (e.g., incomplete digestive tract, open circulatory system, etc.) and assess its viability. Additionally, this assignment was designed to help students understand interactions between animals and their environments and recognize potential trade-offs and constraints. By using the concept of trade-offs, we intend that students come to understand that, in many cases, a physiological process or mechanism cannot be enhanced without another process being diminished. Similarly, we desire that students understand that a constraint is any factor, external or internal, that limits or restricts the range of physiological activity. We developed the assignment as a project-based approach to student learning that involves instructor-directed small group collaborative work (3). However, the assignment could be modified for problem-based learning (3).

This assignment also works well in a variety of institution types and for different academic levels of students. Slightly different versions of the assignment were given in two semesters by each of the authors at their institutions. Collectively, students in these 8 sections were freshman through seniors and were mostly but not entirely Biology majors (some had previously taken only one course in general biology, whereas others had completed upper-level biology courses); students attended private or public and research-intensive or primarily undergraduate universities; and classes ranged from 4 to 27 students. Overall, the majority of students found the assignment to be both challenging and fun and reported that it helped them understand system integration, responses to the environment, and trade-offs and physiological constraints.

The Assignment

The fictional animals. Early in the semester, students were given instructions for the full assignment. The basic premise was that in the year 2146, biodiversity is dangerously low and the United Nations has developed a machine that randomly creates animals with one of two designs for several body systems or other physiological aspects. One example is a homeotherm with unidirectional ventilation, an open circulatory system, an excretory system that secretes only, and an incomplete digestive tract. The systems and their possible designs varied depending on the content and focus of the course (Table 1). In most of the classes, students flipped a coin to determine which of the two possible designs for each system their animal would have; otherwise, the design was determined in advance by the instructor using a binary random number generator or by students drawing options out of a hat. Instructors ensured that no two students or groups had the same combination of systems.

Guidance through the analysis. The three primary learning goals of the assignment were for students to *1*) understand system integration, *2*) recognize effects of adaptations relevant to the environment, and *3*) consider potential trade-offs and physiological constraints. The project typically replaced previous, more traditional assessments as part of the final exam or as homework assignments. Students had four or five systems

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Table 1. *Body system design options used*

	Ventilation Direction	Circulatory System	Excretory System	Digestive Tract	Body Temperature
Design choices					
Vertebrate and invertebrate content	Unidirectional	Open	Filters and reabsorbs	Complete	Homeothermy
	Bidirectional	Closed	Secretes only	Incomplete	Poikilothermy
Alternates for vertebrate only content		In series	Can concentrate urine		
		In parallel	Cannot concentrate urine		
		Complete anatomic division			
		Incomplete anatomic division			

assigned to them and worked as individuals or in groups of two to five to create and analyze their animal (students and faculty members typically preferred working in groups). In most of the classes, the options for two more closely linked systems were determined at the same time (e.g., circulatory with respiratory and digestive with osmoregulatory) after the two units were covered in class. This approach was slightly preferred over having the design of each system predetermined and given to students all at once. To assess the compatibility of the two systems and the compatibility of new systems with each other and previously assigned systems, students were given questions for discussion (Table 2) during class and/or to submit as assignments. In most sections, class time was allotted for students to discuss each pair of assigned body systems (20–30 min of three different class periods) and further time was spent in individual consultations with the instructor as needed or students working together outside of class. The option was given to change a system if it was not compatible with another system. However, in most versions of the assignment used, all possible animals would be viable without the need to change the design of a system. The students were not made aware of this, nor seemed to suspect it.

Final report. At the end of the semester, students submitted a report describing the fictional animal and discussing the compatibility of the originally determined systems, whether any systems were changed and why, and the environment of the animal (Table 3). Students were asked to describe the animal: vertebrate or invertebrate, body design (general body segments, type of symmetry, etc.), limbs and other appendages, its type of outer body covering (e.g., thin moist skin, scales, etc.), approximate size, its habitat, how it is affected by and how it navigates its environment, and any other features of their choosing. In the majority of the eight sections, the report was authored as a group, but one section preferred to work as groups in analyzing their assigned systems and then individually create their own specific animals. In the guidelines given for all courses, it was emphasized that the animal could not closely resemble any extant animal. Drawings of the animal or its body systems were optional in some sections and required in others (Figs. 1 and 2). Reports were assessed with the grading rubric shown in Table 4 or a slightly modified version.

Outcomes

In 3 of 8 sections, 47 students total were surveyed at the end of the semester with a common set of open-ended questions on their opinions of the role of the assignment in meeting the three learning goals (Table 5). Institutional Review Board (IRB) approval from each institution was obtained for each survey administered (University of New Hampshire IRB no. 6244, Rice University IRB no. 851181-2, and Niagara University IRB no. 2015-084). These open-ended questions revealed that

Table 2. *Questions discussed and/or assigned to guide students through the analysis*

Set	Questions
1. After circulation and respiration	Does the circulatory fit with the respiratory system? Why or why not? Your explanation cannot be only because the combination already exists in a real animal. It might be helpful to draw a diagram of the systems, to help you figure it out. This diagram may be included in your report.
	If not, think about what combinations would work well together. But, you may want to decide which one you should change later on, based on the other systems.
2. After the excretory systems and digestion	Does the excretory system fit with the digestive system? Why or why not? Your explanation cannot be only because the combination already exists in a real animal.
	With this in mind, do you need to change its circulatory or respiratory system and, if so, how?
	If the excretory and digestive systems do not fit together, which one should change in order to accommodate the animals' circulatory and respiratory systems?
3. After thermoregulation	Do you think it can actually conduct its thermoregulation strategy given the design of its other four systems? Why or why not? Your explanation cannot be only because the combination already exists in a real animal.
	If not, what should it be?
Additional questions given with each question set above (considering two systems at a time, for each combination of systems.)	What might be an adaptive advantage of the combination of the systems you were assigned?
	What might be an adaptive disadvantage of the combination of the systems you were assigned?
	What trade-offs in function and efficiency might be seen in the interaction between systems?
	What constraints might be placed on the physiological processes of each system by the combination of anatomic structures found in your animal?

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Table 3. *Additional instructions for the final report*

List the original systems your animal was assigned. Explain why they were or were not likely to work well together. Use the seven questions above (from laboratory discussions) as a guide to outline your explanations. Note: You will not get credit for explaining that systems work only because those systems are present together in a real animal. You must explain how/why the systems work together in your fictional animal.
If you needed to change one or more of your systems, describe this. What systems did your animal end up with? Why would this work better than the original animal? Describe for each change made. You cannot get credit for changing a system only to make it fit into a complete animal that you have already imagined, an environment, or a real animal that you modeled your animal after. You can only change a system because it is not compatible with another system.
Describe an environment it would thrive in (earthly or otherwise). Be specific (e.g., deep ocean, temperate forest, arctic tundra, Mars, etc.). Explain why the animal thrives in that environment. Include what elements of its climate are compatible with the animal or how the animal functions and how it is affected by and navigates/lives in this particular environment.

the vast majority of the students surveyed reported that the assignment helped them understand the integration of systems, interactions between animals and their environments, and possible trade-offs and physiological constraints (Table 5). Their self-reports were corroborated by the authors' impressions from reading the assignments, although we did not have a baseline assessment of their abilities in the learning goals before the assignment.

Students usually earned strong scores on the final report, based on the points described in the grading rubric (Table 4); however, they did not always perform well initially in the question sets or they needed a substantial amount of help from the instructor to do so. Instructors provided different levels of guidance to help students understand system integration: for example, allowing students to submit multiple versions of answers to the question sets or engaging in lengthy discussions before submission. Therefore, the score on their final report may indicate a greater ability to analyze the animal than the students possessed on their own without contributions by the instructor. However, student comments in the surveys also suggested an improved ability in the three learning goals, especially systems integration, as well as a better understanding of each system alone, as follows:

> Choosing the environment forced us to think of all the systems together and . . . made the animal more of a reality to us, instead of just a collection of systems.
>
> We had to figure out how to make sometimes unconventional systems work together which means we had to understand how each system works on its own.

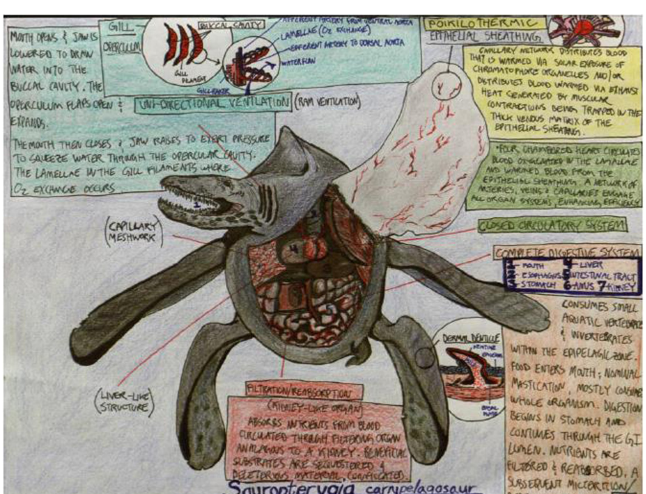

Fig. 1. Drawing of a fictional animal from one report including diagrams and descriptions of some of the body systems. [Used with permission.]

> . . . [I]t caused me to connect the lectures to one another rather than just know them separately.
>
> . . . [I]t was really cool to realize that some physiological factors affect multiple systems/functions in different ways and to have to balance those effects (for example body size affects things like thermoregulation, metabolic rate, the amount of food/water it needs, breathing rate, excretion, etc.).

Student comments also illustrated their beliefs that the assignment helped them better understand trade-offs, physiological constraints, and the role of the environment in animal physiology:

> . . . I know[sic] longer have the misconception that animals have the best functions for their environment.

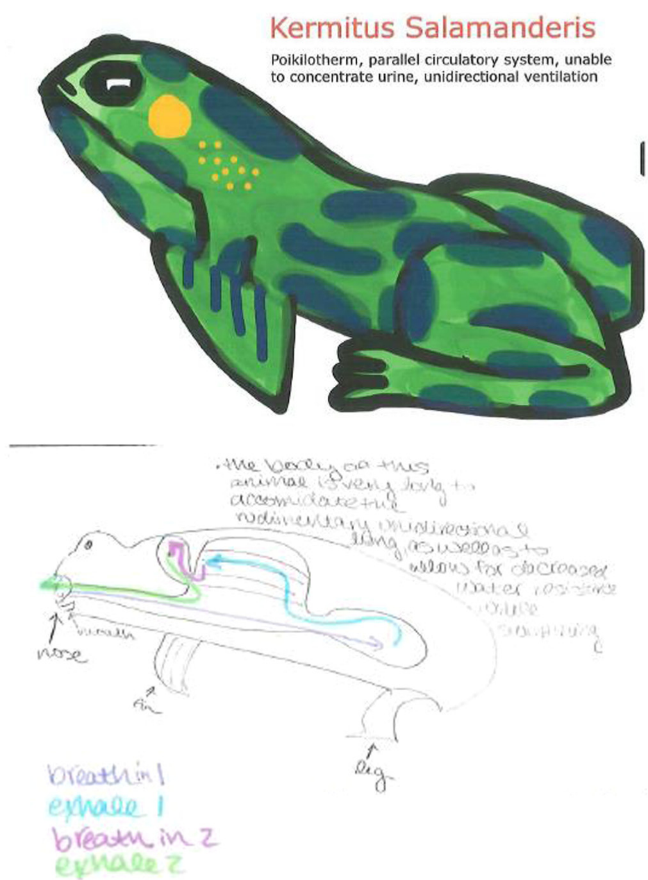

Fig. 2. Drawing of a fictional animal (*top*) and its "rudimentary unidirectional lung" and direction of air flow during respiration (*bottom*). The writing above the animal (*bottom*) states "[T]he body of this animal is very long to accomidate [sic] the rudimentary unidirectional lung, as well as to allow for decreased water resistance while swimming." [Used with permission.]

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Table 4. *Grading rubric for the assignment*

	Characteristic (Point Value)	Earned
System integration (50%)	Systems and thermoregulatory strategy are compatible with each other as described in the final version of the animal for ____. All 5 systems (20) ____; 4 systems (15): ____; 3 systems (10) ____; 2 systems (5): ____; 1 or 0 systems (0): ____	____/20
	The descriptions of compatibility explain why they work together:	____/30
	____ Reasoning logical and explained fully for the 5 systems (30)	
	____ Reasoning flawed or incomplete for 3–4 systems (20−29)	
	____ Reasoning flawed or incomplete for 2–3 systems (10−19)	
	____ Reasoning flawed or incomplete for 0–1 systems (0−9)	
	Systems integration total	____/50
Changes to original animal (20%)	Changes made to system types were necessary for ____. All changes (10): ____; most changes (6−9): ____; half changes (5): ____; little change (1−4): ____; no changes (0): ____	/10
	Explanations of why changes were needed were complete and logical for ____. All changes (10): ____; most changes (6−9): ____; half changes (5): ____; little change (1−4): ____; no changes (0): ____	____/10
	If applicable (if not, total is out of 80), changes to original animal total	____/20
Environment (15%)	____ Specific environment is appropriate for animal (6)	____/6
	____ Nonspecific environment is appropriate for animal (2−5)	
	____ Environment is not appropriate for animal (0−1)	
	Explained how animal and its systems are compatible with the environment ____. Logical (6): ____; illogical or incomplete (2−5): ____; illogical and incomplete (0−1): ____	____/6
	Description of how animal functions/lives/is affected by environment	____/3
	____ Present and consistent between the animal and its environment (3)	
	____ Present but inconsistent between the animals and its environment (1−2)	
	____ Absent (0)	
	Environment total	____/15
Overall description (10%)	Backbone, body design, appendages, covering, size, etc. selections	____/8
	____ All consistent within the animal and its physiological systems (8)	____/2
	____ Some inconsistent within animal or with its systems (3−7)	
	____ Most or all inconsistent within animal and/or its systems (0−2)	
	____ Drawing/description clear and informative (0−2)	
	Overall description total	____/10
General criteria (5%)	____ Writing style clear with proper grammar and spelling (0−3)	____/5
	____ References cited with appropriate format (0−2)	
	General criteria total	
Total		____/80 or ____/100

> . . . an animal may not have the best systems from an outside point of view, but they fit in with the environment they live in.

The assignment seemed to help some students understand concepts in animal physiology related to evolution and diversity. Many of the fictional animals had body system combinations that were not that of any extant animal. It was sometimes helpful for us to remind the students that it could be that there are no known extant animals with the combination of body systems of their fictional animal because of evolutionary constraints, not necessarily because the animal would not be viable. After students determined the animal would be viable, some may have realized that there are many versions of animals that could exist but do not, because of limits of evolution rather than only physiological constraints. One comment seems to reflect this:

> More like an appreciation of diversity and just how many solutions can be applied to the same problem!

According to the student survey and faculty observations, the primary difficulty was learning system integration, which involved determining whether one system would work with another system or if one needed to be changed. Some went about that task by determining whether there were extant animals with the same body systems as their fictional animal. Therefore, we emphasized that in the explanations of system compatibility and the justification of a change to a system, students could not use information from extant animals (Table 3). In addition, we needed to provide students with a lot of guidance and assistance in thinking about the relationship between any two systems. Some students explained that they did not know where to begin. While our students finding these concepts difficult is consistent with previous findings discussed

Table 5. *Responses from the end-of-semester, open-ended student survey questions used in three sections*

Question	Students Whose Response Included "Yes" %	Students Whose Response Included "Yes" Number of Students/Total
Did designing your fictional animal help you understand how physiological systems function together and are integrated?	95.7	45/47
Did choosing the environment where you animal would live help you understand how physiological systems work together, so the animal can response to environmental conditions and challenges?	88.9	40/45
Did you gain a new of deeper awareness and appreciation of trade-offs in function and efficiency as well as physiological constraints placed on an animal in its environment?	89.4	42/47

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above (1), they appeared to gain ability in system integration from the assignment.

In summary, this assignment where students had to determine the viability of a randomly created fictional animal improved students' self-reported abilities in integrating body systems and in understanding the role of the environment, trade-offs, and physiological constraints. Based on anecdotal feedback, students found the assignment challenging but fun. Many students enjoyed the creative input needed to create their animals. As instructors, we very much enjoyed reading about and seeing images of the menagerie of creatures that our students designed.

Versions of this interesting project are suitable for a variety of physiology classes. To improve student achievement of the learning goals, it may be helpful midway through the semester to have each group present their analysis of system compatibility to the class, so students can hear other examples of critical thinking. Similarly, it may be helpful to have the class "practice" analyzing and creating an animal first, perhaps with using systems not included in their assignment to avoid redundancy. Another activity that could be added is for students to present their animals to the entire class at the end of the semester. More time spent during class and in one-to-one conferences with the instructor discussing the implications of different body system designs on the animals would also likely be beneficial. Each of these enhancements should reinforce or deepen our students' ability to think integratively about physiology, not only within each body system but across body systems.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

S.A.B., W.H.C., B.B.-A., and P.A.H. performed experiments; S.A.B., W.H.C., B.B.-A., and P.A.H. analyzed data; S.A.B., W.H.C., B.B.-A., and P.A.H. interpreted results of experiments; S.A.B. prepared figures; S.A.B. drafted manuscript; S.A.B., W.H.C., B.B.-A., and P.A.H. edited and revised manuscript; S.A.B., W.H.C., B.B.-A., and P.A.H. approved final version of manuscript.

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