An Approach to Improving and Evaluating Creative Scientific Thinking Skills in an Undergraduate Animal Physiology Course

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Abstract: Building creative scientific thinking skills is a difficult process for many undergraduate students who often experienced science as a collection of facts in high school. This paper describes an attempt to improve those skills in an undergraduate Animal Physiology course at a liberal arts college. A combination of experimental design exercises, primary literature reading, in-class discussions, the writing of a grant application, and exam questions oriented toward experimental design was used to help students gain skills in asking and answering scientific questions. Although mastery of creative scientific thinking cannot occur in only one course, progress was measured by comparing student responses to an open-ended inquiry session during the first week of class with responses to a final exam question and with the final grant application. Students showed improvement in generation of a testable model, experimental design, and prediction of results. Less improvement was seen in generation of alternative hypotheses and analysis of assumptions upon which their models were based. Small numbers of students for this study limit the statistical analysis.

Introduction

The study of science at the undergraduate level involves several sometimes conflicting approaches. Many introductory classes emphasize content knowledge – gaining an understanding of the information scientists have already gathered through observation and experimentation. Laboratory sessions are designed to introduce students to research techniques and sometimes encourage students to be innovative in their approaches to problem solving (see for example, Rivers, 2002). Reading and discussion of primary literature helps students learn more about the thought processes active scientists use in answering interesting questions about the world around them. For most students, however, the acquisition of content knowledge can override the more creative side of science at the early stages of education. To overcome that, professors must actively engage students in creative, critical thinking processes that will encourage scientific thinking at a higher level; they must specifically teach scientific process along with the content. As Neil Lutsky put it, “The challenge is to engage students in a way that effectively introduces them to the important disciplines of a field, motivates further mastery of those disciplines, and strengthens judgment and perspective about the value and limitations of those disciplines.” (Lutsky, 2004)

A comparative animal physiology course for undergraduates can be an ideal place for professors to establish a learning environment that emphasizes the creative, critical, scientific thinking process (Rivers, 2002). Students' inherent interest in their own bodies often generalizes well to an interest in the structure and function of the bodies of other animals. They naturally begin to ask such questions as “Why would it be advantageous for an elephant to have a trunk whereas I only have a short nose?
Why might it be advantageous for a bird to generate concentrated liquid waste whereas a freshwater fish generates dilute urine?” This paper describes a semester-long approach to encouraging critical analysis of the speculations students make in such situations, in other words, to encouraging a scientific approach to problem solving. Changes were made to the entire course to reinforce these skills based on the premise that students only learn to do something well if they practice in several contexts (Science for All Americans, 1990).

**Learning Goals**

Developing measurable learning goals that target critical thinking skills can be a challenge. The specific goals outlined for students enrolled in the course described here were based on a summary presented by Batzli *et al.* (2006). They were:

1) to generate testable models based on an observation of a phenomenon or information provided in writing,
2) to generate and evaluate alternative hypotheses based on observations or reading,
3) to design experiments that would adequately test the models they generated,
4) to identify important variables and assumptions associated with the models they generated and the experiments they designed, and
5) to predict the results of experiments.

These are all portions of the scientific approach to problem solving that can be easily overlooked in general discussions of a subject or in laboratory projects. For example, it is not unusual for students to read about how vertebrate muscles contract before they have ever considered all the possible ways that muscles could contract. Once scientists have settled upon a particular model, the alternative models are not always presented to the students, and students are not encouraged to generate them on their own. The emphasis is on the “facts” rather than on the thinking process that led to our current understanding. Because animals have evolved to have a variety of solutions to many environmental challenges, the study of comparative animal physiology provides a good forum for considering some of these alternatives.

Another example of emphasis on the thinking process involves helping students learn to distinguish between a model and a hypothesis. Scientists often use the word model in a fairly broad sense to describe a set of structures and the important relationships between them. For example, the fluid mosaic model of the cell membrane describes the overall structure and function of cell membranes. However, the term hypothesis is more commonly used for a specific, testable idea. For example, we might hypothesize that hydrophobic molecules can cross membranes more quickly than hydrophilic molecules in the absence of specific channels. To test the efficacy of a model, many specific hypotheses would need to be tested. If one hypothesis does not hold up to scrutiny, then alternative hypotheses might be tested. Again, the emphasis is on the scientific thinking process, which includes speculation and thinking in the alternative. An important step in the process is the prediction of outcomes, which allows a preliminary evaluation of the adequacy of a hypothesis and an experimental approach before formal testing is done. This often reveals flaws in the assumptions or missed variables, leading to a re-evaluation of the hypothesis or the experimental design.

**Environment and Approach**
At Transylvania University, a liberal arts college with about 1150 undergraduate students, Animal Physiology is a junior/senior level biology course taken by many biology majors. The class of 8-20 students traditionally meets for three one hour lecture/discussion sessions per week with the class divided into two smaller groups for a three hour laboratory period once a week. To emphasize the scientific thinking process throughout the course, changes were made in the laboratory, in the class meetings, and in exams. Similar to the approach presented by Rivers (2002) in which the laboratories for a comparative animal physiology course were modified throughout the semester and the approach taken by DebBurman (2002) in which scientific writing was emphasized throughout an entire term, opportunities to engage in creative, critical thinking were repeatedly incorporated into the course, with periodic assessment of student progress. These included open-ended laboratory experiments, a major experimental design exercise, frequent speculative questions for class discussion, and exam questions which required model generation and experimental design. Many opportunities were provided for students to share ideas and approaches throughout the term, including formal peer evaluation of work generated by other students in the class.

Clearly, it is unreasonable to think that one course could or should be the only source for learning the scientific process. However, an attempt was made to measure student progress during this single-semester experience based on methods outlined by Batzli et al. (2006) and Ebert-May et al. (2006). It is hoped that in addition to demonstrating the value of this approach in one course, this paper may encourage a broader implementation of systematic teaching of scientific process throughout biology curricula.

Revisions and Assessment Plans

To address the student skill learning goals outlined above, a series of exercises, assignments, and exams were given throughout the term. During the first laboratory session, which occurs on the first or second day of the term, a baseline level of scientific thinking was estimated for each student through an open-ended laboratory project. The only instructions given to the students were as follows:

You have been given several termites, several types of ink pens, and a pile of paper. There is some evidence from previous studies that termites can follow a pen trail. You have 30 minutes to work with the materials provided and record observations. Friday in class you will turn in a two to three page, single-spaced paper in 12-point font which
1) describes your observations
2) presents a model (written and/or visual) of the phenomena you observed
3) describes one or more feasible explanations for what you observed
4) describes variables and/or assumptions that are important to your explanations
5) describes one or more experiments which will test your explanations
6) predicts the results those experiments
This assignment will not be given a numeric grade, but will count significantly toward your laboratory participation grade in AP.
The assignment is to be done individually without discussion with other students.
Student performance on the termite exercise, which was based on a laboratory posted by Abbott (2006), was evaluated using a scoring rubric (Appendix A). Students were scored from zero to four on model generation, description of alternative hypotheses, experimental design, identification of important variables and assumptions, and prediction of results. Although this scoring rubric was used only by the professor in evaluating a starting point for scientific thinking in the course and not given to the student, the students were given the opportunity to discuss the termite exercise during lab the following week. A discussion of models and alternative hypotheses was encouraged, with students sharing their best ideas and being encouraged to constructively criticize each other’s approaches to the problem.

Also during the second laboratory session, students worked as a group to design an experiment to test the effects of juvenile hormone on mealworm pupation (Facey, 2005). Background reading for the laboratory gives some information about mealworms and insect hormones. The students were expected to design a simple experiment that would identify the critical period for juvenile hormone disruption of pupation. During the experimental design discussion, the professor stepped out of the room, forcing the students to use their own organizational and communication skills to determine the central assumptions and variables. This experiment spans several weeks, and requires that students consider what sort of information will be gathered and how that information will be recorded and analyzed. In other words, some prediction of the results is necessary to successfully carry out the project. Later in the term, groups presented their experimental design and results to the entire class, providing another opportunity for discussion and feedback. Assessment of the project took the form of a written reflection by each student, evaluation by each student of the work done by their entire group, and notes taken by the professor throughout the project and during the student presentations.

Classroom exercises

A third mechanism used to encourage critical scientific thinking throughout the term was regular classroom exercises and homework problems. Some of these problems were presented as “think-pair-share” exercises during class. Others were given to groups of three to four students during class time, and others required that students consider the problems individually or in groups outside of class, writing their answers in the form of a short essay (1-2 pages) to be turned in at the beginning of the next class. Those essays were often used as starting points for class discussion.

One example of such a project was having students draw their own neuron by putting together various sizes of cylinders and spheres, and then predicting the magnitude of polarizations in various portions of the cell membrane at various times following current injection at a particular location in the cell. Students hypothesized about the mechanisms behind membrane polarization changes and made predictions about the effects of stimulating at various locations on the cell, including on dendrites, on the soma, at the axon hillock, and on the axon itself. Then the students taped their neuron drawings, of various shapes and sizes, together into a network and make predictions about interactions in a circuit.

Another example was to have students work in groups of 3-4 to describe the structure and function of a particular type of muscle based upon their reading in the textbook, i.e., a mammalian cardiac muscle, an insect flight muscle, a frog
gastrocnemius, etc. Then members of different groups were paired and asked to exchange the structure and function of their two types of muscle. For example, what would happen if a muscle with the structure of an insect flight muscle were used to try to carry out the function of the frog gastrocnemius? This exercise forces students to consider alternative approaches that sometimes seem ridiculous, but often have some surprisingly good points. It forces thinking outside of normal assumptions to help students critically analyze relationships.

**Grant project**

The largest project used during the term to facilitate improvement in creative scientific thinking was a grant application written by each lab group of two to four people. This project, worth 25% of the students’ grade in the class, began with each group using their textbook, biology encyclopedias, physiology reference books, and the *Annual Review of Physiology* to generate a list of ten topics related to physiology which intrigued them. Students were encouraged to consider comparative questions, but could choose human and/or disease-related questions if those got them the most excited. After spending about a week doing initial research on the topics, students narrowed those lists to the top three ideas, and then to their topic choice. The students then used a combination of the primary literature, reviews, and their own imaginations to come up with a research question or a set of related questions that would form the basis of a research project. That project was written in the form of a grant application, including an abstract, specific aims, background and significance, project design (including detailed methods and data analysis plans), expected results, references, a time-table, and a budget estimate (see Appendix B). Twice during the term drafts of different parts were turned in to the professor for feedback, and once the projects were exchanged with other groups for formal peer review (see Appendix C). At the end of the term, each group gave an oral presentation on their grant application as well as turning in the final paper. Students were graded on organization and writing as well as on the project itself. The grant projects were assessed for scientific thinking using the same rubric as used for the initial termite laboratory (Appendix A). This approach provides an alternative way to encourage involvement of students in experimental design when there are restrictions on time, equipment availability, and money (see McNeal *et al.*, 1998, for other useful approaches to experimental design in physiology classes).

**Exam Questions**

Exam questions provided further reinforcement of creative thinking and experimental design. Others have shown that tying expectations of active learning and problem solving to grading within a class increases student motivation (Huang and Carroll, 1997). When questions appear on an exam, students seem to take the issues being emphasized by the professor as important. If the exam questions merely asked for recall and summary of information about physiology, the students would not have placed emphasis on learning the thinking skills throughout the course. The following is one example of an exam question used to encourage creative thinking:

*Last Tuesday morning (Halloween), you got a call from Dean Pollard. He said that although he loves his job, he has way too much to do and really needs some help. In the spirit of a helpful Transy student, you offered to make him an assistant, to be nicknamed FrankenDean. You hurried into the laboratory and raided the refrigerator, which was full of great biological structures. You put*
together an almost human-like creature. The only problem was that you could only find a teleost (bony fish) heart in the fridge, not a human heart. The dean was in a hurry for help, though, so you said “what the heck!” and put the fish heart into FrankenDean. What challenges might FrankenDean face as a result of having a fish heart? What rewiring of the regulatory system for the heart would you do to try to overcome these challenges?

The final exam was given in the form of a take-home, open-book examination. All four questions required that students synthesize information from various aspects of the course and one in particular asked students to work with the ideas of experimental design and creative thinking.

Despite your last fiasco (when you blew up the entire block, research building and all!), Joe of Joe’s Bar, Grill, and Research Company has decided to give you one more chance as director of research. His latest observation is that people who eat sushi while drinking beer show more symptoms of inebriation than people who eat Szechwan beef while drinking beer. He hypothesizes that this has something to due with the rate of digestion of sushi as compared with the rate of digestion of Szechwan beef. Describe a model of digestive function that would account for Joe’s observation. Then choose one specific hypothesis that arises from that model and describe how you could test that hypothesis.

In addition to a letter grade given to students for their final exam, the answers to the this final exam question were assessed for model generation and experimental design using two of the scoring lines from same rubric that was used to evaluate the initial laboratory exercise with termites and the grant project (Appendix A). Since the students were only asked to generate one hypothesis based on a model, the hypotheses were scored on a four point scale based on four criteria: whether the hypothesis derived clearly from the model, whether the hypothesis was specific, whether the hypothesis was testable, and whether testing the hypothesis would actually test for validity within the model. Students could earn 0, ½, or 1 point for each of the four criteria for a maximum score of 4 points.

In summary, a series of assignments and exercises was used throughout the entire term to help students practice scientific thinking skills. Since feedback is considered essential to student learning (Science for All Americans, 1990), students were given both formative and summative evaluations throughout the term to reinforce the importance of these skills. An evaluation rubric was used by the professor at three stages to gather information about student progress in creative scientific thinking.

Assessment

Data were gathered over a two year period from all 28 students who took Animal Physiology. In the initial assessment of creative scientific thinking using the termites, most students presented a very simple model that did not contain sufficient information to be carefully tested or to make good predictions. (See Appendix A for the assessment rubric and Table A for a summary of scores.) Few of the students chose to use visual or graphical representation of relationships, but rather summarized their models in just a few sentences. Although one student presented several alternative hypotheses, weighing the pros and cons of each, most students presented only vague descriptions of alternative explanations for the observed phenomenon. A few students did not present any alternatives. In their descriptions of experimental design, most students either described only one experiment or designed experiments that would not
distinguish between alternative hypotheses. From the explanations, this appeared to be because the students either were not really considering alternative hypotheses or because they were missing the important variables that could distinguish between alternatives. Students seemed able to identify some of the important variables, but did not give much explanation of their importance or the impact those might have on their experimental outcomes. Most students were able to predict the results of their experiments, but few were able to consider those potential results in light of the limitations imposed by their experiments. Overall, the students seemed to understand the basic steps involved in the scientific method, but to lack depth of analysis and an eye for detail. They were clearly not comfortable with considering alternatives, but were seeking a single, simple solution.

Table A: Mean Scores and Ranges for Initial Scientific Thinking Explanation Assessment (n= 28)

<table>
<thead>
<tr>
<th></th>
<th>Model Generation</th>
<th>Alternative Hypotheses</th>
<th>Experimental Design</th>
<th>Variables and Assumptions</th>
<th>Prediction of Results</th>
<th>Total Score (Max. 20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Score</td>
<td>1.96</td>
<td>1.96</td>
<td>2.11</td>
<td>1.82</td>
<td>1.50</td>
<td>9.39</td>
</tr>
<tr>
<td>Range</td>
<td>0-3</td>
<td>0-4</td>
<td>0-3</td>
<td>0-3</td>
<td>0-3</td>
<td>1-15</td>
</tr>
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</table>

In the later assessments, most students showed improvement in their scientific thinking skills. The students worked in small groups on the grant project, so individual achievements cannot be distinguished from the group. In the first term, there were four groups while in the 2nd, five groups completed the project. Average scores are shown in Table B. Most groups did a reasonable job describing their model, although many groups would have benefited from a graphical representation of the proposed relationships. One group failed to consider any alternative hypotheses, but just proposed a single hypothesis for testing. Experimental designs were generally quite good, although the students lack of experience and depth of knowledge about the areas of proposed research sometimes showed in neglecting important variables or ignoring some of the assumptions inherent in the research techniques. Most students did a good job predicting their results and describing the implications of those results in the context of their model.

Table B: Mean Scores and Ranges for Grant Project Assessment (n= 9 groups of students)

<table>
<thead>
<tr>
<th></th>
<th>Model Generation</th>
<th>Alternative Hypotheses</th>
<th>Experimental Design</th>
<th>Variables and Assumptions</th>
<th>Prediction of Results</th>
<th>Total Score (Max. 20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Score</td>
<td>3.11</td>
<td>1.98</td>
<td>3.04</td>
<td>2.11</td>
<td>2.20</td>
<td>12.43</td>
</tr>
<tr>
<td>Range</td>
<td>2-4</td>
<td>0-3</td>
<td>2-4</td>
<td>1-4</td>
<td>0-4</td>
<td>10-17</td>
</tr>
</tbody>
</table>

A comparison of rubric scores between the initial termite explanation and the grant project are shown in Figure 1. Due to the small number of students studied, it is not surprising that statistically significant differences were not observed. It is clear,
however, that the semester’s learning activities did not have an impact on the consideration of alternative hypotheses and had minimal impact on the consideration of variables and assumptions the students chose to present. However, a trend was apparent toward improvement in model generation, experimental design, and prediction of results.

Figure 1: Mean rubric scores from the early semester pretest (blue) and the final grant project (red). Error bars represent the standard deviation.

On the final exam question described in the previous section of this paper, most students showed improvement in their ability to generate a reasonable model, but several struggled with creating a more complex model than had been asked in the initial termite exercise. Most students were able to generate a clear hypothesis based upon their model, but the experimental design aspect of the exercise did not show much change over the initial evaluation. Under the pressure of an exam, the improvements seen in experimental design between the initial test and the grant project were not evident. The students often gave very simplistic experimental designs which did not address specific aspects of the model, but rather would just result in confirmation of the data upon which the question was based. Results are summarize din Table C.

<table>
<thead>
<tr>
<th>Table C: Mean Scores and Ranges for Experiment Final Exam Question (n=26)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Generation</td>
</tr>
<tr>
<td>Mean Score</td>
</tr>
<tr>
<td>Range</td>
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<tr>
<td></td>
</tr>
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* Two students failed to answer the section of the question relating to the hypothesis and experiments, so these numbers are based on only 24 students.

Students demonstrated a good attitude toward learning throughout the course, working closely with each other and sharing learning goals. The teams of students made mistakes in designing their mealworm hormone experiments, particularly in
planning the data gathering and analysis stages of their experiments sufficiently to
gather useful, interpretable data. However, once the groups discovered their problems,
they worked together well to overcome them, sometimes restarting the experiment from
the beginning with a more organized and thorough approach.

Was the approach effective?
When beginning this experiment, I expected that students would make the
greatest progress in experimental design. The biggest surprise was what level if
difficulty students had in developing a model that could describe the phenomenon of
interest, and then use that model to generate testable hypotheses. Given a model, they
could generate hypotheses rather well, but they seemed to lack the ability to work with a
specific hypothesis within a broader framework. Without that framework, it is difficult to
focus experimental design in useful fashion.

Given that observation, it is apparent that students made limited progress in
development of a testable model during the semester. They become more comfortable
working with broader ideas, and demonstrated the ability to generate a good
hypothesis. Given sufficient time and input from lab partners, the students were able to
carry that idea all the way to good experimental design. However, at the end of the
term when pressed to design a good experiment under a time constraint, they fell back
onto the same types of over-simplistic experiments using only human subjects that they
were most comfortable with. It is clear that teaching students to have the confidence to
be creative scientific thinkers takes more than one term, but rather a consistent, on-
going effort throughout their undergraduate and graduate careers.

What changes might be made to make it more effective?
On the first iteration of this project with assessment, there were only nine
students in the class and minimal explanation was given beyond the handouts found in
the appendices. Based on the initial observations, it appeared that students were still
struggling with the relationship between a model and a hypothesis and with the idea of
considering alternative hypotheses. Therefore, additional discussions of these ideas
were included in class time and more formative feedback was provided. For example,
during the lab session following the evaluation of the termite observation write-ups, 20
minutes of time was taken to discuss some of the models and alternative hypotheses
that had been suggested by members of the class. The next week in class, students
were given an example of a visual representation of several possible models for a
biological phenomenon (vesicle trafficking in the Golgi apparatus) and asked to
generate hypotheses based on each model. The class discussed hypotheses arising
from each model and experiments that would differentiate between the alternative
hypotheses within and between models. In addition, soon after deciding on their focus
for the grant project, each small group of students met with the professor. They were
asked to bring a visual representation of their model to that meeting. During the
discussion, group members were asked to identify places within their model that could
be tested to determine the validity of the model. Alternative hypothesis and alternative
interpretations of expected results were discussed.

To work on the student’s weakness in more sophisticated experimental design,
pushing students to step out of their comfort zone may be necessary. For example,
having students design experiments that cannot use human subjects or requiring that
they come up with at least three experiments that take alternative approaches to testing
the same hypothesis might provide additional practice. To help students consider alternative hypothesis, I am considering classroom exercises in which one group of students presents an idea for an experiment, and then other groups must not only critique the experiment, but also propose alternative explanations for the expected observations.

In conclusion, helping students step out of their fairly rigid boundaries of thinking to be more innovative and creative as scientists is one goal of a liberal education. Effective classroom and laboratory exercises as well as out of class assignments to promote that goal are challenging to design and implement. The repeated experimental design exercises used in the class presented here provide starting points, but are not sufficient to change thinking patterns in only one term.

Acknowledgements:
Encouragement to formally assess student learning in these projects came from colleagues involved in the First II initiative and Project Kaleidoscope, both sponsored by the National Science Foundation. Terry Derting and Diane Ebert-May provided particularly helpful insight and guidance. Transylvania University, through the Kenan fund, supplied the time and funding to allow me to write this article. Joni Wiseman and Janice Hall’s support and wisdom in the laboratory have been invaluable.

References:


*Science for All Americans*, 1990, American Association for the Advancement of Science, New York, Oxford University Press.

**Appendix A: Scoring Rubric**

<table>
<thead>
<tr>
<th>Model generation</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model accurately represents a feasible explanation based on the information provided; Model presented both verbally and visually</td>
<td>Model accurately represents a feasible explanation based on the information provided; Model presented either verbally or visually, but could use better explanation or more detail</td>
<td>Model misinterprets some of the information provided or does not account from significant information; Model explanation is reasonable, but incomplete</td>
<td>Model misinterprets much of the information provided or is completely inaccurate; Model explanation or representation is unreasonable</td>
<td>Not done</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Alternative hypotheses</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Several feasible alternative hypotheses are presented along with the pros and cons of each</td>
<td>Several feasible alternative hypotheses are presented, but with insufficient explanation for clarity</td>
<td>Several alternative hypotheses are presented, but they do not all fit well with the data presented and/or lack logical explanation</td>
<td>More than one hypothesis is presented, but one or none are reasonable based on the data presented</td>
<td>Not done</td>
<td></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Experimental design</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple experiments which address varying aspects of the model are presented; Experiments are feasible and would produce usable results; Choice of methods is well justified</td>
<td>Multiple experiments which address varying aspects of the model are presented; Some of the experiments are feasible and would produce usable results; Some of the methods are well justified</td>
<td>More than one experiment is presented, but experiments may significantly overlap in their focus or choice of methods may be poor OR only one well-designed experiment is presented</td>
<td>Only one experiment is presented and its justification and methods are poor</td>
<td>Not done</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Important variables and assumptions</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Important variables are clearly identified; Underlying assumptions</td>
<td>Most of the important variables were identified; Most of the underlying</td>
<td>Some of the important variables were identified and some assumptions were presented, but</td>
<td>Minimal presentation of variables or assumptions with little or no</td>
<td>Not done</td>
<td></td>
</tr>
</tbody>
</table>
have been presented along with their implications for data interpretation
assumptions have been presented along with implications
with minimal explanation of implications OR one variable or assumption incorrectly identified
explanation of implications OR several variables and/or assumptions were incorrectly identified

Prediction of results
Feasible predictions are presented both verbally and visually; Limitations of the data are considered in the analysis
Feasible predictions are presented either verbally or visually; Some limitations of the data are considered in the analysis
Predictions are presented, but may have some logical inconsistencies; Limitations are considered in a cursory fashion
Inaccurate predictions are made; Limitations are not considered
Not done

Appendix B: Grant Project Assignment

Goals:
1) Read about current research in physiology
2) Be creative in scientific inquiry
3) Formulate a testable hypothesis
4) Learn about specific research techniques in depth
5) Consider a research project from idea to data analysis
6) Demonstrate critical thinking skills in physiology

Assignment:
Each lab group will generate ideas that interest them, narrow that list, and research the ideas before selecting a research topic.
Each lab group will write an NSF-style grant application with the following sections:
abstract, specific aims, background and significance, project design (includes detailed methods and data analysis plans, expected results, references, time-table, and a budget estimate).
Each lab group will review applications from two other groups.
Each lab group will give a 15 minute presentation about their research proposal to the entire class near the end of the term.

Schedule:
Tuesday, 1/22: Brainstorming session with your group during lab time
Friday, 1/25 List of ten ideas turned in during class
Tuesday, 1/29 Two paragraphs summarizing ideas and introductory research for each of the ten ideas due during lab time
Friday, 2/1 Decision on your grant project due in class. Include five annotated references related to your topic. You will turn in a short paper from the group that describes the process you went through in deciding on your project. How did you generate research questions? How did you identify
the important variables that might require study? What assumptions are you making in working on this project?

Friday, 2/22  Background and significance and specific aims due to Dr. P
Tuesday, 3/4  Grant drafts due for exchange with other groups. You must include the background and significance, specific aims, a strong draft of the detailed project plan, and a list of at least eight references

Tuesday, 3/18  Peer reviews of grant drafts are due. Bring two copies of your review – one for Dr. P and one for the reviewed group. At the top, list the names of the members of the group being reviewed and the names of the members of your group, which did the reviewing.

Tuesday, 4/1 and 4/8  Wrap up work time for the papers and presentations
Wednesday, 4/9  Morning lab groups present their grants in class
Friday, 4/11  Afternoon lab groups present their grants in class
Friday, 4/11  Final grant paper due (include copies of the proposal and reviews, and the grant draft and peer reviews)

More detailed instructions:

*Generating ideas:* Physiology is full of outstanding questions about animal function! Think about things that you want to know more about, things you have always been curious about, things that are related to your future career plans, etc. Look through your textbook to see what ideas or general subject areas you can see. Go to the library and look at the encyclopedias of life science. Look at the *Annual Reviews of Physiology* journal online from the library. Search Medline for articles related to animal function, choosing a topic and reading some abstracts of papers to determine what kinds of questions scientists are currently asking. DO NOT limit your thinking to only humans or only disease states. Consider questions that range from the molecular level to the population level. Interactions between species are also fair game. In other words, let your questioning mind set to work!

When you have an idea, begin with “what do I know”, then move to “what do I not know”, “what things are not known by the scientific research community”, and finally, “how can I find out”?

*Deciding what to work on:* Use the questions at the end of the section on generating ideas to get you started in the thinking process. After you have a list of ideas, use Medline to search for review articles related to your subjects. Read through those reviews, looking for the analysis of the experts on what questions are outstanding in that area. Discuss with your group members ideas and hypotheses about the answers to those questions. Consider the assumptions that are being made by researchers in the field. What alternative hypotheses can you generate? After extensive research and discussion with your group, decide on the research topic that gets your group the most excited.

*Writing the background and significance:* Do extensive research on your topic. Find out who is doing research in this area and exactly what questions they are asking and how they are asking them. This section of the grant is meant to bring the readers into tune with your thinking. Make sure you give the background on what others are doing and how that led to your assumptions and your hypotheses. Are there several alternative hypotheses that could be considered? Why is it important to the understanding of
animal function to distinguish between them? Why will answering your question(s) further our understanding of animal function? Is there a clear application of your expected results? In this section, you are essentially explaining to the reader the model you have in your head.

Writing the specific aims: This is basically an executive summary. You need to state your research goals in two or three single sentences. When the reader learns more about your project in the project design section, he/she should be able to very clearly link each experiment with the specific aim it is trying to achieve. Specific aims are the detailed hypotheses you are trying to test based upon your model. The specific aims will be presented in the grant application before the background and significance, but you will write them afterwards.

Writing the project proposal: This is the meat of the grant. This is where you lay out your specific experiments, including all the details about how they will be done. Give details on the numbers and types of animals to be used and/or the techniques to the used. Be sure to thoroughly reference this section. Diagrams are often helpful in showing experimental design. Include the rationale for your design, the details of the design, and the form in which the data will be gathered. A plan for data analysis is also an important part of experimental design. Exactly what data will you gather and how will you analyze it? Will the data you gather clearly address your hypotheses? Will they validate or refute your model? All experiments have limitations; be sure you have explained those clearly. Often doing several experiments of different types can help to overcome the obstacles to clear interpretation that come from only one experimental design.

Choosing good references: Begin with review articles. These will give you an overview of a certain area, usually presented by an expert in the field. A good review includes not just information, but also an analysis and synthesis of that information, relating one study to another and speculating about what is missing. From the review, you can get good ideas about narrow, specific problems that are amenable to further research. Also, use the references given throughout the review to lead you to the detailed articles that will tell you the specifics. Since you are not an expert in physiology techniques, you want to find information from people who are. Look for primary references that are using the techniques you are interested in, but asking slightly different questions. Look for primary references that are asking a similar question, but used different techniques. From these, spin your own approach to the questions.

Annotated references include the full citation and a one paragraph summary of the main points of the paper and its relevance to the research topic being considered.

Predicting the results: You should have a visual image in your mind of what you think the results will be – how your results will fit with your model. You may have several alternative images. You need to have predicted results to be able to design a good data analysis approach. Both verbally describe and visually depict your predicted results.

Drafting a rough budget: Try to consider what sorts of equipment, supplies and personnel you will need. Use the internet to search for a rough idea of prices on these things. Who will do the work and how much time is needed to get it done? Graduate
students will cost you about $15,000 a year in grant money, sometimes more. Post-doctoral fellows will cost you about $30,000 a year. Undergraduate researchers can contribute for very little money, but need to have quite a bit of time and help from graduate students and postdoctoral fellows.

*Estimating the timetable:* Most grants are written with a 2-5 year duration. Will you be able to get your work done in that time? Don’t forget that this is rarely the only thing people are working on. Nothing ever works the first time you do it, so plan on several months to work out all the kinks before you are really gathering good data. Don’t forget data analysis and writing time.

*Writing the abstract:* After you have finished everything else, try to summarize the goals of the project, design of the experiments, and expected results in a single paragraph. This will appear at the beginning of your grant application, but is the last thing you write.

*Presenting your work:* You will be given 15 minutes to summarize your work for the class. You will not be able to tell us everything, but we want to know something about your motivation for asking these particular questions and the way you are doing it. How are you going to do the experiments? What potential problems do you anticipate? Imagine that you are verbally presenting your application to a review committee; you need to “beat out” your competitors for the money. Wow us!

*Peer review:* The peer review of the proposal should focus on the relevance of the questions asked, the appropriateness of the research techniques chosen, the clarity of the goals, and the likelihood that the research project will clearly address the specific aims. Feedback from your peers is the best possible way to be urged to question all of your assumptions. Give them detailed written feedback, just as you would like to get from others. This is not just an opportunity to nit-pick about writing style and grammar, but a chance to ask questions that will help your classmates to think more deeply and advance their learning. Take advantage of this part of the process! Giving and getting feedback are both important processes in science.

*For additional reading:*


**Appendix C: Peer Review Guide**

Does this grant application clearly and thoroughly summarize the relevant scientific literature?

Does this grant application clearly indicate where this project fits within the framework of the current literature?

Does this grant application clearly explain the significance and implications of the project?
Are the aims/goals clear and appropriate?

Is the choice of model organism(s) explained and appropriately selected?

Do the authors demonstrate a good knowledge of the procedures to be used in the experiments?

Are the procedures thorough, clear, and appropriate?

Have any important aspects of the experimental design been neglected?

Can the authors reasonably expect to carry out the studies as planned in the time indicated?

Have the authors explained what data will be gathered, how it will be compiled, and how they intend to analyze it?

Have the authors indicated what results they expect to get and why?