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Teaching Science: Design of a Master's Level Biology Course

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Abstract

In this work, I describe the development of a Master's level microbiology course which uses an active learning approach to encourage the students to think scientifically about the course material and gives the students training in experimental design, data analysis, literature research and scientific oral and written presentation. The course combines a case study approach with an inquiry based lab. I discuss how the students are formatively assessed in the course and how this becomes a motivational tool. Finally, I discuss the feedback from the students in terms of course evaluation.

Keywords: Inquiry based labs; Case study; Biology education; Higher education; Science education

Introduction

A common approach to teaching in natural science is to simply use the traditional lecture format to transmit information from lecturer to student. This format can work reasonably well with a charismatic teacher and students who are self-motivated to both listen in class and spend hours after class learning the material. Although I was taught this way and began my career teaching this way, there are multiple problems with this methodology. Besides the obvious problems of non-charismatic lecturers or unmotivated students, students' classroom time is not spent learning, but rather recording information. Granted, students may memorize parts of the information in class but most of the learning is done outside of class. In the age of massive readily-available sources of information online and in books, it can and should be questioned whether this is an efficient use of classroom time. In addition, this approach does little to encourage scientific thinking and problem solving. Students need training to reason in a scientific manner, e.g., forming hypotheses, experimentation, and data analysis.

In this paper, I will describe in detail one of the courses I have developed, Prokaryotic Molecular Microbiology, which has been running since 2005. I will discuss how different aspects of the course are supported by the pedagogic literature and discuss the practical aspects and results (in terms of student evaluations and student performance) of this course.

Science Education

Most definitions of science describe a system of knowledge or knowledge obtained through a systematic method (or scientific method). For example, the Merriam-Webster dictionary (http://www.merriam-webster.com) :

- **a:** knowledge or a system of knowledge covering general truths or the operation of general laws especially as obtained and tested through scientific method **b:** such knowledge or such a system of knowledge concerned with the physical world and its phenomena"

In other words, most definitions of science include the method of gaining knowledge as well as the knowledge itself in the word science. This may be self-evident for many of us in the sciences, but it lies at the center of our educational problems in science. Science is not an unrelated set of facts that can be memorized. Rather it is a framework of understanding into which facts can be inserted or deduced.

Teaching science then is very easily modeled on a constructivist platform of education (for a thorough discussion of constructivism see Biggs and Tang 2007). A major point of constructivism is that students construct knowledge by connecting it to prior knowledge and frameworks. Science works much the same way. The scientific approach utilizes previous knowledge to create hypotheses and experiments and new information is incorporated into an overall body of knowledge. Occasionally, in history, new information will change the framework entirely but most often new information can be tied to previous ideas and usually will lead to new connections and further predictions.

Given this very close relationship between a popular learning theory and the scientific method, how then could we be failing to teach science to our students? There is general consensus that in most countries, education in the STEM topics is failing to produce students with the skills and interest in science needed for an increasingly technological world (e.g., Alberts, 2005, Merkel, 2012, Savkar and Lokere, 2010, National Research Council, 1997, 2003, Wood, 2009). The reasons for this are complicated and sometimes politically charged, but a major reason is that science is not often taught with this constructivist way of thinking. Often, students are presented with fact-based lectures which fail to engage the students' previous knowledge and fail to encourage creation of a mental framework to increase conceptual knowledge of the topic.

This failure has been documented most thoroughly in the physics classroom using data gathered using the Force Concept Inventory (FCI, Hestenes, et al, 1992). The FCI is used to test students' knowledge of basic concepts and misconceptions on Newtonian physics. The data clearly show that although students can solve exam questions requiring mathematics, they are simply memorizing the equations without deeply understanding the underlying concepts. This has led some universities to change the way in which physics is taught to encourage conceptual knowledge and deep understanding in addition to memorization of equations. Similar problems have been documented in biology courses (Wood, 2009 and references therein): students know key vocabulary and can repeat key concepts but lack the ability to apply this knowledge to new problems or demonstrate a clear understanding of basic concepts.

This Work

The aim of this paper is to describe and reflect on the development of a Master's level course in Microbiology that tries to integrate the scientific method into every aspect of the course. Specifically, the course uses a case study approach as well as an inquiry/research based laboratory. The aim of this course structure was to avoid the problems mentioned above and encourage lifelong learning of biological concepts and scientific thinking.

Course Introduction

Prokaryotic Molecular Microbiology (PMM) is a 15 hp course taken by students in the first year of their Master's degree or the last year of their Bachelor's degree. The student composition of PMM is a mixture of Swedish native students, Swedish non-native students and exchange students from both EU and non-EU countries. Class size has varied greatly due to changes in the total number of applicants to all science related courses. The course is designed for a maximum of 18 students, but has been run with as few as 10-12 students in a few of the last 10 years. The course runs full-time for 9 weeks.

Students at this level are about to enter a Master's level laboratory thesis project ('examensarbete') of typically 60 hp (9 months). Subsequently, the majority of these students intend to either enter a research based PhD program or research focused employment. For this reason, the course was developed with the intention to introduce students to current methods and topics in prokaryotic molecular microbiology and prepare them for a research career. The first goal is straightforward and could be done with many pedagogical techniques. The second goal though is more complicated. Some of the issues and learning objectives I wanted to address in this course were:

- Students must be able to read current research articles
- Students must be able to both preform experiments but also interpret their (usually) imperfect data.
- Students must be able to design experiments based on hypotheses and previous work.
- Students should be able to work in groups to facilitate problem-solving as well as experimental work.
- Students should be able to explain their work both orally and in written papers.

To this end the course was designed as summarized later in this paper, but first I will describe the component parts of the course and the reasons why they are included.

The Case Study Approach

The Case Study method in its broadest definition is 'telling a story with an educational message' (Herreid, 1994). As such, case studies span a wide range of methodologies and approaches from a lecture format to problem based learning. In science teaching the most accessible way to explain a case study formatted course is that it uses specific examples of research topics to teach general principles. The story is the research topic.

Anyone who writes a scientific paper or gives a scientific lecture knows the importance of telling a 'good story' and that story is a very powerful educational tool. Stories draw the student into the topic by making them curious about the end results in much the same way as a mystery novel draws the reader into the story as they become more invested in the characters and ultimately they want to know what really happened. An interesting scientific paper or topic can inspire the students to engage more in a topic than a (often boring) recitation of facts.

In this course, the case studies are original research articles chosen to illustrate the required concepts or knowledge I want the students to learn in the course. Because they are very specific, it is important that the students make the connections between the specific topic and the general principles. If the students do not do that on their own, I, as the teacher, always conclude the discussion with a mini-lecture designed to make that connection explicitly for the class.

In this course the students work in pairs to present two different topics during the course. They generally are given the topics about two weeks before the presentation and are expected to work on the topic for approximately 20 hours before they present. During the presentations, the class is not passive.

They are expected to have read the main article and each class, 4 students are randomly chosen to ask questions about the topic; this is done to a) keep the class involved through discussion and b) to encourage deeper understanding of the topic.

I am often asked, 'why don't I just lecture about these topics?' I could lecture about the topics more efficiently, cover more material and possibly give clearer explanations than the students generally give. This is true, but the more important question is 'would the students learn as much if I lectured?' Evidence suggests that this is not the case. Students in a traditional lecture setting are often given no opportunity to use their critical skills of analysis, they are not problem solving, nor learning to read research papers and they are certainly not gaining practice in presentation. In other words, they *might* gain equal knowledge of the topic by my lecturing but little or none of the important transferable skills listed in the previous section. Indeed, evidence suggests that students exposed to pure lecturing do not gain as much knowledge of the topic and understanding of the concepts compared to active learning approaches. For example, one study documented 30% normalized learning gains in a developmental biology course by substituting 30-40% of the traditional lectures with more student centered activities (Knight and Wood, 2005). Several other studies within biology courses have similarly found increased learning with less lecturing (e.g., Armstrong, et al, 2007, Freeman, et al, 2014, Smith, et al, 2005, Udovic et al, 2002). The effectiveness of case studies in science specifically, rather than other types of student centered activities, have less documentation, but that literature is positive (e.g. Dori, et al 2003, Yadav, et al, 2007)

Exam

The exam was included in PMM to meet a specific assessment requirement. A major course aim is to teach how to read research papers, analyse data and extract information for future studies or research. The case study presentations and their assessment aims to mold the student's development in this regard, but since the assessment is based primarily of the student's oral presentation, usually done in pairs (although graded individually), I felt an independent, individual assessment of the student's progression in these learning objectives was needed at the end of the course. To this end, I developed an exam modeled on the interrupted case study. As far as I am aware this is an unusual *(unique?)* assessment tool, so I will explain it in detail.

The interrupted case study (Herreid, 2005) is somewhat similar to classic PBL except that it focuses more on problem solving and less on information retrieval. Information is given out piecemeal to students for analysis and discussion before the next set of information is given out. For example, students may be given the introduction to a research article and asked to define the research problem and state the author's hypothesis. This can be done in small groups, in class or as homework. Once this step is accomplished and discussed with the teacher, the next set of information is given out. For example, the methodology used in the article might be given out and the students asked to design an experiment using the methodology to test the hypothesis. Once this has been discussed the article's experimental design will be presented to the class and they will be asked to predict the results if the author's hypotheses are correct. Lastly, data will be presented and the students will be asked to interpret the results and make conclusions. This last step can of course be repeated with each experiment in the article.

It should be obvious based on this description, that the interrupted case study is designed to reinforce the student's use of the scientific method. The scientific method is explicitly demonstrated at every step. The beauty of this pedagogic method is that most research articles can be easily adapted to this form of teaching with minimal preparation time on the part of the course leader and because the majority of time for the methodology is spent in small student groups, it can be done outside of class and it does not require significant in-class time, unless the teacher feels this would work better in class. I have used this sort of case study only sparingly in my courses; my impression is that it is a method that works most effectively if only used 1-3 times in a given course, because the workload on the part of the students is very high. I suspect if overused it might lead to students becoming exhausted with the approach and not putting in as much effort over time, however, it should be possible to redesign it slightly to be used more regularly.

I have used this approach to design an exam format. As I stated above, I want to assess whether my students have learned to critically read an original research article in the course topic. Each year, I find a recent paper whose topic has not been explicitly discussed in the class, but which overlaps with regard to methodology and approaches to the class topics. This paper is then edited to create a kind of interrupted case study (without the interruptions!). The students are given parts of the paper, and asked to make hypothesis, analyse data, and make conclusions. The exam itself becomes a 'teaching moment' in that the students have not read about this topic previously and will learn about the topic by doing the exam. Because the topic is new to the students, it also means I can make this an 'open book' exam. Students can bring any textbooks, notes, etc that they would like. They are only limited by not being able to use the internet during the exam. The reason for this limitation is that they would easily find the actual article which would be a great advantage in the exam as it would remove much of the thinking needed to complete it.

Inquiry Based Laboratories

Laboratory work can serve several objectives. The most obvious is to train students in experimental techniques. Although this is important, focusing only on this aspect is a lost opportunity for teaching student's other skills that can enhance the students' learning and employability. Specifically, experimental design, data analysis, the scientific method, as well as general skills such as working as a team can be added to laboratory classes to teach multiple skills at once. I would argue that it is this second set of skills which will remain most relevant for many students throughout their career as experimental techniques often are replaced by newer methods or automated systems. As an example, I was taught how to sequence DNA when I was a student. The methodology I used has been completely replaced by automated machine based services using different basic principles. What I did learn in those laboratories was how to interpret my data and how to design an experiment. At their worst, traditional labs teach only methodology and do not even attempt to teach higher level cognitive skills.

Inquiry based laboratories aim to incorporate the skills I describe above into student labs. Essentially, an inquiry based laboratory, from the students' point of view, starts with a problem or question within the topic. Students then need to first gather information about the problem to define it in a clear and specific manner, then design an experiment and do the experiment. Finally data is analyzed and conclusions made. Substantial evidence exists that inquiry based labs increase students' motivation and improves student outcomes with respect to data analysis and experimental design (Myers and Burgess, 2003, Luckie, et al., 2004, 2012, Wood 2009). A variation of this type of laboratory is a research based laboratory where the student's results are completely unknown and tied to active research questions. There is some recent evidence that these types of labs are even better at teaching students the secondary skills mentioned above as well as improving the retention of students in the sciences than inquiry based labs not tied to a current research problem (Russell et al., 2007, 2010).

From the teacher's point of view, inquiry based labs often can be designed with only small modifications to pre-existing 'cookbook' laboratories chosen for a specific technique or topic. Simply by rewriting the lab, one can incorporate student thinking and inquiry. For example, rather than simply giving students a recipe and having them blindly follow it, the framework of the lab can be changed so that it is phrased as a question. The actual lab work will be identical, but the students will need to think about the aims/questions and why they are doing the protocols.

As a simple example of what I am describing, we can use the gram stain of bacteria. Different bacteria score as positive or negative in this very common test. A 'cookbook' way of demonstrating this lab would be to give the students the ingredients and have them follow the protocol. The inquiry based approach would be to give the students the problem of unknown bacteria and ask them to design the experimental protocol using the gram stain method. The students would need to realize that they should use controls, i.e., known gram positive and negative strains, as well as their unknown in order to make valid conclusions. This addition to the lab would take trivial amounts of extra time if organized properly but adds a major learning element to the lab.

Since PMM is a class of at most 18 students and they are at the Master's level, we can extend this way of thinking even further. Each year the students have a single problem based lab to work on. The students work in the lab almost every day for approximately 8 weeks. The overall project is for the entire class. For example, we may look at the effect of 10 different growth conditions on gene expression as a class. Each pair of students will be assigned two of these growth conditions to examine during the lab. Thus during the laboratory, everyone will likely be using the same methodology (e.g., measuring gene expression) but the precise conditions in each student group is different. The reason for doing this is that it gives the students a sense of 'ownership' over their work: each student group has their own condition and their own project. From the point of view of lab organization, supplies and lab assistant time in teaching methods, there is only a slight increase since there needs to be some flexibility in the precise schedule for each group (e.g., one group may need to repeat an experiment).

The problems addressed in the laboratory are 'real'. By that I mean that the final results are not known by anyone and have never been published. I always try to choose problems where I know they should get a result, but the actual experiment has never been done. An example of the lab manuals is available upon request, but as an example, one year the students tested the effect of a set of *E. coli* mutants on expression of the gene *uspB*. From the literature, I expected all of these mutants to have some effect, but no one knew how gene expression would be altered by the mutations in the conditions tested in the lab. This use of a real scientific problem is used to increase the student's excitement and interest in the laboratory.

Poster

The poster is used to supplement the content of the course with newer information and according to the students' interests. The students are given two choices when choosing their topic. They can choose a topic within the field that interests them and suggest an appropriate recent starting research article for their poster (or I will help them find one). Alternatively, the students are given a list of recent research articles covering topics that were not explicitly discussed in the course. Most of these articles have been chosen by me by skimming the last 6 months of the appropriate journals or using recommendations in the Faculty of 1000 website (http://f1000.com/prime). The students then have the responsibility to read the article, do background reading and create a poster that explains the topic to the class. Besides giving the opportunity to present more material to the class, this work teaches the students to focus their presentation to the most essential points. A poster generally includes only 3-4 key experiments whereas a typical research article can include 10-20 experiments. The poster is an individual task and the students will present their work on the last day of class. The remainder of the class ask questions at this presentation.

Overall Format of the Course
The information in this section is given to the students at the start of the course.

This course uses an 'active learning' approach which means that course content will be guided by the course leader, but that much of the learning in this course will require active participation from the students. This means that attendance in all parts of the course is mandatory except under exceptional circumstances. The aim of using this 'active learning' approach is to give the students a deeper understanding both of prokaryotic molecular microbiology and scientific research. This approach will be extensively explained during the introductory weeks of the course.

-Introduction: The first week of the course will consist of lectures introducing methods, techniques and general information about molecular microbiology. Lectures generally are interspersed with small problems.

-Case Studies: The next ~5 weeks will be devoted to case studies. Case studies will be assigned to pairs of students who will prepare a seminar on a specific research article addressing an important topic in prokaryotic molecular microbiology. The students not presenting are expected to have read the case study and come to class prepared to ask questions and discuss every case study. Points will be given both for the presentation and for participation from the remainder of the class. Following each case study the course leader or other faculty member may give a 'mini-lecture' on the general topic presented in the more specific case study.

-Laboratory: Simultaneously with the case studies, an 8 week lab project will be done. This laboratory is a 'real' research project where students will learn techniques in molecular microbiology and just as importantly will learn to do research in as close to a real research setting as possible in a course. Much of this lab will be done in a self-directed format. A lab assistant will be available to give advice and guide the research, but students are expected to work independently. At the end of the lab, the students will write a research article describing what they have done and their results. Students will work in groups but will write their own lab report.

-Exam: An 'open-book' exam will be given in the second last week of the course.

-Poster Presentation: Several days before the end of the course, each student (working alone) will display a poster on a topic in prokaryotic molecular microbiology that they have chosen themselves. These will be reviewed by all students and several faculty members. On the last day of the course we will have a poster session where the student presents their topic briefly (12 minutes) and faculty members and students will discuss each of the posters for approximately another 12 minutes.

Grading
Points will be accumulated throughout the course. 60 points are needed to pass ('G') and 80 points are needed for 'VG'. The maximum points for each part are as follows:

- 20 p Case study 1 (16p presentation+4p participation)
- 20 p Case study 2 (16p presentation+4p participation)
- 20 p Lab Report
- 20 p Exam
- 20 p Poster (16p poster +4p participation)

Detailed grading for the parts will be presented in class (and are described below).

General Reflections and Student's Perceptions on the Course

The overall student reaction to this course has been very positive with an average overall course evaluation score of between 9-10 out of 10 (or 4,5 out of 5 in the newer grade scale) each year I have taught it in this format from 2005-2015. The interesting part of the course evaluations however is not that the students gave it positive scores, but rather that they gave it positive scores at the same time that they commented that the course was very difficult and had a heavy workload. Some typical comments illustrating this are below:

- *It was 'harder than other courses but also more satisfying'*
- *'I was a bit stressed but it was very stimulating'*
- *'I think that even if it was a lot (of work), that was good because it is then you do your best.'*

My own perception of the course mirrors these comments. I am often truly amazed by the large amounts of effort these students are motivated to put into the course and even more impressed at their development throughout the course. By the end of the course, the majority of the students are able to critically analyze published research articles on new topics, design experiments, and have progressed to the point where I think they are ready to begin supervised research projects.

Overall the results of this course demonstrates the huge impact that motivation can make on student outcomes, as predicted by learning theory.

a) Case studies

The case studies are used primarily because they train the students in several of the learning objectives. Besides the obvious: mastery of the topic, the approach emphasizes use of the scientific method, trains the students in reading research papers and gives them practice in presentation skills. Because, for most people, oral presentations are frightening, there is strong intrinsic motivation for the student to come to class prepared and do a good job.

The requirement to ask questions of other student presentations is crucial to this methodology. I participated in one earlier version of this course which did not have this requirement and it was not successful. The students paid little attention to the presentations and the general mood was one of disinterest and boredom. In contrast, by the mid-point of PMM, I find myself having to stop students from discussing so much just so that we can get through the material in the allotted time. Generally a 45 minute presentation becomes close to 1.5 hours (excluding a break) with questions and discussion. Thus, half of the time is actual group discussion of the topic, rather than a lecture formatted presentation. The rewarding of points for questions allows this to evolve during the course. During the first few classes, students are generally hesitant and ask a minimum of questions, but as their confidence grows in their own analytical abilities, questions are asked more frequently and often without reward (only some of the students get points for questions each session).

The case studies are not without flaws however. One particular problem is that students do not always come prepared, by reading the paper, to discuss the topics of other students. I have not found an easy way to fix this problem, but the requirement for asking questions generally motivates the students to at least participate in the discussion and listen carefully to the presentation. Attendance at all the case studies is mandatory and the 'punishment' for missing a case is that the student must write a one page summary of the topic. In general, this works quite well to guarantee full participation.

One must also be aware of a problem that can arise and that is when a student does a poor job at presenting the material in a case study. My obligation is to the class as a whole and I am always prepared to step in and explain the topic to the class. I try to do this in the nicest way possible but it must be done in my opinion. I do warn the students that this could happen at the beginning of the course and that they should not be too upset as I will also do this if the concept is a particularly difficult one that needs further explanation.

b) Laboratories

The labs are generally positively received and I think they are crucial to the overall success of the course. The idea of doing real research is inspirational to most of the students and can be very positively reinforcing. Substantial evidence exists that inquiry based laboratories like this one leads to better learning outcomes (e.g., Myers and Burgess, 2003, Luckie, et al, 2014), however, the laboratory tends to be the most complicated aspect of this course. Because I try to mimic a 'real' project as much as possible, failures and mistakes can occur. To some extent, I think this is fine as failures and mistakes are part of real experimental science! However, some years we have had too many problems with the lab work which tends to frustrate rather than inspire the students. In addition, because I frequently change the topic of the lab, some years we have had too much work for the students to do in the lab. It is a balancing act and I find I have to be ready to improvise every year. It does, however, get easier to design with practice. Finally, it should be noted that the lab assistants are crucial to the success of this lab approach. Disinterested lab assistants can ruin a traditional lab and can be even more destructive in this sort of lab. For this reason I try to involve the lab assistants in the planning of the lab at the earliest possible time so that they are invested in its success.

c) Assessment

The assessment in this course is formative: students receive feedback from each part of the course as quickly as possible after the activity. The grades for each case study and exam are given within a few days of the presentation or exam. The lab report and poster are due on the last day of the course and are graded after. It is particularly clear that the fact that the students get feedback from their first case study early in the course is important in their development. Students who have done poorly hear what they did wrong and those on the right track are encouraged to continue in that path.

The grading for the different activities is subdivided into a clear rubric which is given to the students. For the case study (total 16 points), they are scored on 4 equal aspects: effort (i.e., amount of research), understanding (i.e., ability to answer questions, demonstrate understanding of the topic), presentation (clarity of slides, organization of the talk, etc.) and the last 4 points are given for their written summary. Similarly there is a rubric for the poster that includes the poster itself, their presentation and ability to answer questions about the poster. In general, I found that having these clear grading schemes along with written comments on each activity have led to little dissatisfaction or disputes about grading. I think it is important to have such a clear scoring rubric since grading a presentation could become quite subjective, or at least appear that way.

The feedback from the students on the 'interrupted case study' exam has been interesting. Although it is administered like a normal exam, with a set time, exam guards (proctors) and the formal atmosphere of an exam, I have had many students tell me afterword that 'it was fun!'. They learned a new topic and were led through the process in a natural scientific manner. Generally, the grades on the exam mirror the grades in the rest of the course: students who have done well on case studies and lab reports do well on this type of exam, and vice versa.

Concluding Remarks

This work describes how a course can be designed to encourage students' scientific development using a variety of didactic approaches. It is important to note in this time of economic pressures on our universities, that this course is not more expensive or time-consuming than courses taught more traditionally. Teacher-led classroom hours are decreased slightly and are substituted with an increase in student-centered activities. For example, since the students are expected to spend many hours preparing their case study presentations and reading original literature, fewer lecture hours are needed. On the other hand, the teacher does need to be more available to the students outside of class to give guidance in their independent work. All in all, the time spent on this course (by the teacher) is approximately equal to a traditional course.

This course conforms to current learning theory and the conclusions from studies from the National Research Council (1997. 1999, 2003) as well as numerous respected scientists and the feedback from the students is overwhelmingly positive. It does however require a commitment by the course leader to play an active role in the course's development which is well rewarded by the obvious learning gains of the students and their positive feedback.

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