CRITICAL THINKING IN A NEUROBIOLOGY COURSE

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Critical thinking skills are fostered in an upper level undergraduate neurobiology course in several ways. First, students formulate questions about neurobiology that personally interest them to motivate their thinking critically. Second, critical thinking is defined, and the instructor's goals for the course are clearly stated, at the outset of the course. Third, the instructor models critical thinking, demonstrating how to read the technical literature, and encouraging active discussion of data. Fourth, students are given opportunities to develop this skill through practice. Fifth, assessment of performance in the course reflects a student's success in acquiring the ability to think critically. Though this approach may have limitations, it does improve students' ability to respond effectively to novel problems.

Introduction

There is a growing interest in enhancing critical thinking skills among students in the biological sciences (Allen and Stroup, 1993). Critical thinking may be defined operationally as the ability to assess the truth or falsehood of an assertion by carefully weighing evidence, by recognizing assumptions that may underly one's reasoning, and by taking responsibility for arguing a particular position (Perry, 1970; Mellon and Sass, 1981; Arons, 1976; Allen and Stroup, 1993; Allen, 1995).

Over the last seven years, I have taught an upper level undergraduate/beginning graduate student course called Introduction to Neurobiology. It is an elective course, ranges in size from 12 to 30 students, and is about equally divided between undergraduates (generally Juniors and Seniors), and graduate students. I have gradually introduced a wide variety of changes into the course that foster critical thinking. These changes came from a careful consideration of the educational goals for the course, and the difficulties that students were experiencing in learning the material.

There are several educational goals for the course. I wanted students to get excited about the great advances and new understanding in the neurosciences, and to grasp key concepts in the field. Most importantly, they should be able to teach themselves what they needed to know once they had defined their own area of interest, and to critically assess the information they obtained from the technical literature. The ability to do this would serve them for many years, even after the specific facts of the course were superseded by advances in the field. It would also help them in many other subject areas.

In the first years of the course, students had several difficulties in mastering the material. Many students showed almost no retention of material that had been taught to them, even as recently as the previous semester. Many would attempt to master new material by memorizing it, repeating it back on exams, and then forgetting it in order to repeat this process with later exams, and with other courses. Moreover, many students had difficulty dealing with problems that required them to use material that they had learned previously if it was presented in an unfamiliar context. Exhortations to think critically about material that had not been assimilated led to feelings of anxiety and bafflement on the part of students. These problems were serious obstacles to the educational goals of the course.

The following steps have helped to overcome the difficulties and achieve the goals:

1. Students are motivated to engage in critical thinking;
2. The educational goals of the course, and the process of critical thinking, are explained explicitly at the outset;
(3) Critical thinking is modeled, so students can learn by example how to do it themselves;
(4) Students practice critical thinking to improve their skill in it;

After describing the methods used to achieve these five steps, I will discuss some of the limitations of the approach, and of the course. Despite these caveats, I will argue that this approach has improved the educational experience of my students, and may be of general utility for many other courses in the sciences.

Motivation

Critical thinking, like spinach, may be good for students, but it may not be something they choose on their own. It requires sustained intellectual effort. It can make students anxious. It requires repeated practice to master. Thus, it is crucial to provide students with a positive motivation for engaging in it. The desire to get a good grade in a course, or to please a professor, are unlikely to be adequate motivations for the hard work that is necessary. Moreover, the whole rationale for engaging in critical thinking is that students should be enthusiastically responsible for what they learn, and want to master the skill of critical thinking in order to improve their ability to learn, assess, and assimilate new material.

In order to help students discover their motivation for learning the material in the course, the entire first session of the class is devoted to the following two questions: (1) What question in the field of neurobiology would you like to answer by the end of the semester? (2) What information would you need to know in order to answer that question?

I call on different students, and ask them if they wish to tell us their question. If they do, I ask them to tell me their name and their major in addition to the question they would like to answer. I write the question up on the board, and initiate a discussion about it. Table 1 shows a few of the questions that students asked last year and this year.

If the question refers to a medical condition (e.g., understanding how to cure Alzheimer's disease, stroke, or brain trauma after an accident), I ask them what else they would need to know in order to answer that question. As they discuss the question, they realize that, in order to cure a disease, one must understand its underlying causes, and that it is therefore essential to understand the cellular and molecular mechanisms that go awry and lead to pathology. In order to understand abnormal states, it is generally useful to understand the normal function of the system. Furthermore, the more we understand about a system's normal function, the more likely we are to cure novel diseases. If one can answer "How does it work?", one can answer "How can we fix it?"; but if one only knows the answer to the second question, one may still not be able to answer the first question. This provides a motivation for understanding basic neuroscience even if one's major interest is in medical applications.

If the question refers to an engineering problem (e.g., building a machine that could think, or a robot that could see and move about in a natural environment), I again ask them what they would need to know in order to answer that question. As the students discuss the question, they realize that even simpler animals can solve some of these problems, and that it may be much easier to

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<th>Table 1. Student Questions.</th>
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<td>1. How does the brain build circuits?</td>
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<td>2. What are the mechanisms of long term potentiation, and how do they relate to learning?</td>
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<td>3. Can we surgically repair nerve damage, e.g., spinal cord injuries?</td>
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<td>4. Could we simulate in an artificial system thinking and consciousness?</td>
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<td>5. What are the mechanisms of cerebral damage before and after a stroke?</td>
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<td>6. What neural parameters can be observed in the fossil record, especially in early hominids?</td>
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<td>7. Is there a neural basis for intelligence?</td>
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engineer a solution after looking at the details of a previously solved problem. I emphasize that biological organisms have evolved, so that one cannot assume that their design is either (a) optimal or (b) readily comprehensible to us, but that we may gain valuable insight by studying how they work. If one can answer "How does it work?", one can answer "How can we build something that does the same thing?". The first question is the fundamental one to answer. This helps motivate the study of basic neuroscience even if one's major interest is in engineering applications.

If the questions reflect an interest in basic neuroscience, we discuss the need to understand the cellular and molecular properties of nerve cells, their synaptic interactions, how they are put together during development, their function within small circuits, and their function within large brain systems, all within the context of an animal's body, behavior, and environment. This provides the students with my rationale for the syllabus for the course. More importantly, this first session helps students develop a specific personal motivation for learning the material in the course.

**Goals and definitions**

If students have succeeded in other courses by memorizing facts, or by memorizing problem solving templates, they are not likely to abandon these techniques in favor of a completely different approach. Nor should they. There are many circumstances in which these techniques can be effective for recalling material, or more efficient for solving familiar problems. My goal is to add another tool to their intellectual toolbox, that is, the skill of critical thinking.

To motivate the idea of critical thinking as an intellectual tool, I ask students to imagine a trade school that teaches how to use a hammer, screwdriver, or a drill, by showing slides of these different tools, and describing what they do in lectures. These students are then given multiple choice tests with questions like, "A hammer is used for (a) screwing screws, (b) banging in nails, (c) bending wires, (d) drilling holes, (e) none of the above." Assume a student gets As in this course, and all the other courses in the school, which are taught in the same way. I ask them, "Would you hire a graduate of this school to build you a chair?" They all laugh. Then I say, "But how is it any different if all you know how to do is to answer multiple choice questions? Unless you use the intellectual tools your professors give you, you won't do any better!" This makes them think. It emphasizes that memorization of facts or templates alone will not allow them to deal with real problems. They must use the information, and learn to think critically about it, if they wish to cope effectively with novel, real world situations.

We then discuss the stages that lead to critical thinking, based on ideas developed by William G. Perry Jr. (Perry, 1970; Mellon and Sass, 1981). In this schema, one begins with Dualism, the notion that all statements are either right or wrong, and that truth and falsehood can be determined by reference to an authority. The recognition that there is fundamental uncertainty leads to the next stage, Multiplicity, the notion that truth is personal. Students at this stage will cite the views of different authorities, but will not defend any particular statement. The recognition that evidence is relevant to the value of different statements leads to Relativism, in which a student can cite a viewpoint and the evidence that supports it, but does not have his or her own viewpoint. Finally, the recognition that one must weigh evidence oneself leads to Commitment, in which one actively seeks evidence for evaluating a particular hypothesis, can effectively weigh evidence and reach a decision about its truth or falsehood, and can argue for one's views using logic and evidence. This is the essence of critical thinking. This skill is not just valuable for studying science, but for analyzing more general questions, such as those of public policy.

Having provided the students with an introduction to critical thinking, I explicitly define the goals of the course (described above), and emphasize the centrality of critical thinking to achieving those goals. I stress that a significant part of the first half of the course will be a quantitative introduction to neurophysiology, and this will require students to use mathematical formulae to solve problems. In order to give the students a feeling for the level of mathematical sophistication of the course, I hand out a math quiz. I give the students 15 minutes to complete the quiz, then collect it and hand out an answer sheet, which I briefly discuss with them. I grade the quiz, but do not count it for the final grade. If the quiz indicates that a student has serious deficiencies, I strongly suggest that the student practices problem solving, and seeks tutoring if necessary. Thus, I clearly state my expectations for student performance during the first half of the semester.
In the same class session, I hand out copies of a recently published article in the neurosciences from the journal Science, and spend the rest of the session discussing and demonstrating how one reads the technical literature. First, I talk about the structure of a scientific article, which is generally as stereotyped in form as a sonnet. A scientific article begins with a brief Abstract, and then an Introduction, Materials and Methods, Results, and Discussion. Second, I point out that most scientific writing is, in a sense, a form of fiction. The historical sequence of discovery is eliminated, the blind alleys and false leads are suppressed, and history may be effectively re-written so that the article presents a logical sequence of steps, each one following inevitably from the previous one. Some investigators may actually obtain their results in a completely logical sequence, but most don't, not because they are sloppy, but because they discover that their pet theory was wrong, and that the truth is stranger and more interesting. Third, I point out that scientists can never prove they are correct; they can only ingenuously rule out different explanations by careful experimentation, that is, they can fail to prove that they are wrong. If they do manage to refute their own theories, they have to dismiss them, even though this may be emotionally wrenching. The consolation is that well designed experiments not only rule out theories; they may suggest better ones.

"Is an article correct because it has been published in Science?", I ask the class. "If not, how could it be wrong?" This leads to an interesting discussion on possible sources of error: (a) the authors could have been untruthful; (b) the data could have been misinterpreted; (c) the method used to obtain the data could be flawed; (d) the results might not be repeatable, or (e) the underlying assumptions could be wrong.

How does one read a technical article? A natural tendency in reading these extremely complex articles is to read the Abstract, the Introduction, and the Discussion, in order to understand the claims that the authors are making. Most readers then accept these claims, and ignore the detailed evidence because it is too complicated to understand. This is not the way to read critically. Begin with the Abstract, then look carefully at the Methods, being especially careful to think about their possible limitations. Spend most of the time looking at the Results, and attempt to understand what each figure shows, and whether it actually supports the hypothesis. Are there other explanations for the results? Does the evidence rule out these other explanations, or not? Are there internal contradictions in the data presented? Then it is time to read the Discussion, and see if the authors' claims actually follow from the data. Good scientific articles will attempt to raise and eliminate the most serious objections, and discuss some of the limitations of the conclusions. Good readers may be able to spot unwarranted assumptions, flaws in logic, and experimental limitations in the data. The goal is not to be so critical that all one can see are the flaws, but to have a healthy scepticism about claims, however authoritatively presented, until one has weighed the evidence oneself and come to one's own conclusions.

I then read the Abstract of the article that I handed out, and translate it phrase by phrase into English, providing background information necessary to understand its key points. We look at the figures together, try to understand them, and discuss whether or not they support the hypothesis. We discuss some of the assumptions that the authors have made implicitly or explicitly, as well as other possible interpretations of the data. At the end of the session, I tell the students that I have shown them what I expect them to be able to do by the end of the second half of the semester. Thus, by the end of the second class session the students have a clear sense of the goals and expectations of the course.

Modeling critical thinking
It is not enough for a professor to talk about critical thinking; he or she needs to model the behavior by engaging in it regularly. Handing out and analyzing a technical article is a good start, but if one then relapses into a standard lecture format, the students are likely to relapse into the standard passive learning mode. Modeling critical thinking requires that the professor treat students as potential colleagues who should be respected as sources of information and novel insights. The goal is to develop an ongoing dialogue with students in which they are engaged with the professor in critiquing and assessing data.

In order to engage students in discussions throughout the course, I learn students' names, encourage students to ask questions, and ask the students questions. By asking students to tell me their name during the first few class sessions, by handing back problem sets to students individually, and by keeping the class list with me during
the first sessions, I can usually master most of the students' names within the first four or five class sessions. This indicates to the students that I regard each of them as unique individuals. It also prevents them from lapsing into unobtrusive passivity, since I can call on any one of them by name at any time.

I begin each class by asking if students have any questions. If a student does ask a question, I spend the first few minutes of the session answering it. During the class period, I encourage students to ask questions. If I see a student with a puzzled look on his face, I will ask him if he can ask a question that clarifies what it is he doesn't understand. I treat all questions respectfully, and never denigrate a student for asking a "stupid" question.

I encourage challenging questions that exemplify critical thinking, such as "What is the evidence for what you just told us?", or "What mechanism could account for this phenomenon?", or "How is this consistent with this other material that I learned in another course?", or "Are you sure you got the signs right in the equation you just wrote on the board?". These questions are an opportunity to introduce more advanced material, or an opportunity to be honest about my own mistakes, or the limitations of my knowledge. I publicly correct myself if I made a mistake in something I presented in class, and will come back with an answer during the next session if I didn't know the answer when the question was asked. I will sometimes defer certain questions to after class if they will take me too far afield, or will force me to repeat material that most of the class appears to have grasped.

I regularly intersperse my lecture with questions to the students. I convince them that these questions are not rhetorical by waiting up to half a minute for them to answer, by calling on particular students by name, and by seriously considering their responses. If a student does not prefer to answer, I go on to another, but I may return to this student later in the session. I avoid the "one right answer" syndrome, which discourages creative thinking. For example, during this past semester, I asked students what an animal could do with a visual system that could only distinguish light from dark. I expected that they would say that the animal could distinguish day from night, affecting when it was active or inactive. Instead, one student pointed out that an animal that lives underwater or underground could use this kind of visual system to find the surface, which was a very good answer that I had never thought of before!

During the second half of the course, I hand out lecture outlines in the form of questions [Table 2]. The questions serve as the basis for both lecture and discussion, as well as for the data figures analyzed in class.

### Table 2. Questions as Lecture Outline.

#### Questions for lecture on locomotion

1. What are the problems that need to be solved by a neural system that controls locomotion?
   a. How do the properties of an animal's body affect the way it locomotes?
   b. How do the properties of the environment affect the way an animal locomotes?
   c. In legged locomotion, how does one maintain stability?
   d. In legged locomotion, how does one generate a range of gaits?
   e. How does a locomotion system incorporate sensory feedback?
   f. How does a locomotion system steer?
   g. How does a locomotion system plan movements, especially over rough terrain?

Practicing critical thinking

The ability to think critically is a skill that can be learned and can be improved by practice. For this reason, students are given multiple opportunities throughout the semester to engage in activities that encourage them to solve problems and think critically:

(a) problem sets
(b) "lab" sessions using computer simulations
(c) student-led problem sessions after class
(d) a review exam prior to the midterm, and
(e) data figures to analyze in class.

During the first half of the semester, which emphasizes a quantitative understanding of electrophysiology, students are given weekly problem sets. Two of the problem sets use computer programs: AXOVACS, written by Professor Stephen Jones, (Department of Physiology and Biophysics), and HH, written by Mark Dimaline, Randall Beer (Department of Computer Engineering and Science), and myself. The problems give students the opportunity to calculate, simulate, and explore many of the properties of nerve cells, e.g., their current/frequency characteristics, threshold, refractory period, response to pharmacological agents, ionic conductances, channel properties, signal conduction, and spatial and temporal summation. Some problems can be solved in many different ways. Table 3 shows excerpts from one of the problem sets. As I hand back a graded problem set, I give the student a detailed answer key, so that the student has immediate feedback.

In the last two years, I have introduced additional problem sessions. The sessions are led by an undergraduate who took the course in the previous year, and occur at two different times (one is usually right after class, the other early in the evening). These times are chosen so that, in principle, all students in the class can attend at least one session. During the first half of the semester, the problem sessions are devoted to solving quantitative neurophysiological problems. Students may ask about problems that were on problem sets, but the sessions are not designed to work these problems for them. Students are encouraged to propose problems and work together in small groups to solve them. During the second half of the semester, problem sessions are devoted to analysis of experimental data from articles. Part of the session reviews material covered in class, and part of the session explores new data. I regularly sit in during one of the two weekly sessions, but defer to the student leader, unless he directly asks me to contribute to the discussion, or is inadvertently misleading the students.

One week prior to the midterm, I run a review session during a regularly scheduled class session. Prior to the class session, I write all the necessary equations on the board, along with other information that might or might not be useful. I then hand out a review exam that consists of questions similar to those that are likely to be on the midterm,

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<th>Table 3. Problem Set Questions.</th>
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<tr>
<td>(Excerpt from Problem Set 3, Fall 1995, using the program HH)</td>
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4. In this exercise you will examine the effectiveness of a current input to a neuron as a function of its location on the neuron's dendrites.

   c. Set the injected current for all compartments to zero. What is the minimum current that must be injected into the eight most distant compartments (4, 5, 7, 8, 11, 12, 14 and 15) in order to induce an action potential in compartment 1? What is the minimum current that must be injected into four of the most distant compartments (e.g., 4, 5, 7, and 8) in order to induce an action potential in compartment 1? What is the minimum current that must be injected into two of the most distant compartments (e.g., 4 and 5) in order to generate an action potential in compartment 1? What is the minimum current that must be injected into a single most distant compartment (e.g., 4) in order to generate an action potential in compartment 1? What is the relationship between these different minimum currents? What does this indicate about the importance of spatial summation in determining the activity of a nerve cell?

*d. Design a neuron that can be activated only by one particular pattern of spatial and/or temporal inputs. Note that you can create your own branching neuron by clicking on the soma or any other segment, and then selecting Add Compartment from the Tools menu. Compartments can also be deleted. After you are done creating the morphology of your neuron, you can also choose Renumber segments from the Tools menu to simplify the numbering of your neuron's compartments.
though they may be somewhat easier. Students spend half an hour taking this exam. I do not collect the exam, but I do ask the students to assess how well they would have done if this was their actual midterm. The rest of the session is spent discussing these problems, any other questions the students may have, and reviewing other material. I point out to them different strategies for solving problems, and encourage them to reason qualitatively about the problems, based on the data that is presented. This tends to help them focus their studying, and reduce their anxiety about the exam.

During the second half of the semester, I regularly practice critical thinking about experimental data by handing out data figures as part of my lectures, and devoting a significant amount of class time to discussing them with the students. I will sometimes encourage the students to look at the figures in groups with specific questions in mind before beginning to discuss them. I call on a student after she has had a chance to look at the figure, and ask her to help me understand it. What does the data show? Does it support the hypothesis? What other information would you need to answer the question? Students are initially hesitant to answer, but as they gain more experience, they become more willing to do so, and by the end of the semester can respond with facility.

After the midterm, and at the very end of the last class session, I also hand the students the list of questions that they posed at the very beginning of the semester. We discuss two questions: Can you answer these questions now? Would you ask them in the same way? After the midterm, many students see how they might be able to use what they have learned in the first half of the course to address the questions that most interested them. By the end of the semester, the students feel that they could begin to answer the questions, but they also feel strongly that they should be rephrased. They make many suggestions of ways to make the questions more precise, more specific, and more subject to empirical testing. I point out to them the considerable progress they have made, and congratulate them.

### Table 4. Problem from Midterm Exam.

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<th>Question</th>
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<td>(a) (5 points) Is the postsynaptic potential likely to be inhibitory or excitatory?</td>
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<td>(b) (10 points) Calculate the reversal potential of the postsynaptic potential.</td>
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<tr>
<td>(c) (10 points) Calculate the conductance of the postsynaptic potential.</td>
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<tr>
<td>(d) (20 points) If the resting potential of this neuron is close to the reversal potential of the postsynaptic potential, how can it change the likelihood that this neuron will fire?</td>
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**Assessment**

Perhaps the single most important factor in encouraging students to engage in critical thinking is that a good grade in the course must depend on mastering this skill. If an instructor emphasizes critical thinking, but administers examinations that assess memorization and/or the ability to do small variations on problems that have been repeatedly drilled, students will fall back on rote memorization, or on memorized problem templates. Thus, every form of assessment for this course explicitly requires critical thinking skills. Students are assessed by means of problem sets (described above), a midterm, brief critical thinking questions, a term paper, and a final.

On the midterm examination, students are presented with data-based problems in neurophysiology, and must use quantitative and qualitative reasoning in order to solve the problems [See Table 4]. The midterm requires that students know the different formulae used in neurophysiology. Many of the problems introduce novel information that can be understood based on the material that has already been presented, but requires applying it to a new situation. For example, the question shown requires students to think about the role of "shunting inhibition" - even though this synaptic input will clamp the membrane potential close to the resting potential, by
increasing the conductance of the postsynaptic neuron, it will decrease the effectiveness of excitatory inputs. Once the midterm exam is graded, it is handed back with a detailed answer key, so that students have immediate feedback on their performance.

During the second half of the semester, in the middle of lectures, I hand out critical thinking questions. These are based on the approach of Robert D. Allen, who has used these successfully in large lecture courses (Allen and Stroup, 1993; Allen, 1995). The students are posed a question, and then offered several alternatives. They are asked to choose the best answer, as they would for a standard multiple choice question, but they are also asked to write two or three lines explaining their rationale for accepting or rejecting each alternative. I give the students about ten minutes to do this, collect their answers, and then discuss the question with them. I read but do not grade the responses.

For example, in the lecture on cortical function, I described the results of lesion studies, which suggest that occipital cortex plays an important role in processing visual information, that temporal cortex plays an important role in memory and recognition of objects, that parietal cortex plays an important role in focus of attention and locating objects in space, and that prefrontal cortex plays an important role in organizing and planning behavior over time, and flexibly adjusting it to changing contingencies. I describe one test of prefrontal function that involves giving a subject blocks, and asking the subject to build a four-walled square. Most prefrontal patients build a long single wall. They can recall the instructions of the task, but are not disturbed about their failure to plan ahead and use the material appropriately in order to construct four walls. Then describe the Wisconsin Card Sort Test, in which subjects are given cards which have one, two or three circles, triangles, crosses or squares on them, all of a particular color. The subject is instructed to find a rule for sorting these cards based on whether the experimenter says "Yes" or "No" to a particular card. For example, the rule could be "three objects or triangle", and thus a card with any three objects on it, or a card with any number of triangles would satisfy the rule. Unexpectedly, however, the experimenter changes the rule in the middle of the task. I then hand out a critical thinking question about this information [see Table 5]. Note that the information just presented makes it possible to deduce that the best answer is choice e.

The results of administering these questions regularly are somewhat sobering. Some students can clearly utilize the information that they have just been given in the lecture to deduce the correct answer and eliminate the alternatives. Other students may misinterpret the alternatives, and choose an incorrect alternative. Still other students clearly have not grasped the key concepts, and have no idea how to answer the question. However, as the semester progresses, most students improve.

Students are offered two options for a term paper: they may write a critical review of the literature or a grant proposal. For a critical review, they need to find a well-defined hypothesis that is currently a source of contention in the field (e.g., "Adult neurons are incapable of regeneration", or "Processing of visual information is due to a feedforward hierarchical analysis of features extracted from visual inputs."). They should locate about 5 papers that support the hypothesis, and about 5 papers that do not, and explain the evidence for or against the hypothesis, and ultimately come to some conclusion themselves about it.

For a grant proposal, they should follow the NIH guidelines (which I hand out to them), and answer the following four questions (the text of these questions is from pp.20 - 21, Application for Public Health Service Grant [PHS 398]):

(1) What do you intend to do? (Specific Aims),
(2) Why is the work important? (Background
and Significance),
(3) What has already been done? (Progress Report/ Preliminary Studies), and
(4) How are you going to do the work? (Research Design and Methods).

Students are asked to volunteer to present the contents of their term paper to the rest of the class during the last session or two of the term. Each student has 10 to 12 minutes for their presentation, and then the class asks them questions. Though students tend to be nervous as they speak in front of the class, they generally appreciate the opportunity to discuss the research that they did for the term paper with the class. Their presentations also allow me to expose the rest of the class to many different topics that could not be covered during the semester.

The final examination is open book and open notes, eliminating the need to memorize large amounts of material. It also counts equally with the midterm, problem sets, and term paper, thus making it harder for a student to do well (or poorly) in the course simply by doing well (or poorly) on this single exam. Each question on the exam shows a figure from a recently published paper, and asks variants of the following three questions: (a) What does the data show? (b) Does the data support the hypothesis?, and (c) What experiments would you do next? [Table 6 shows a question from a recent final exam.] Even though the exam is open book and notes, I tell students that they need to carefully review all the material of the course. Otherwise, they will spend most of the exam looking things up and reading, and not spend enough time on their answers. The exam has the complete references for the articles from which the figures are taken. Since students may take their exams home (their essays are written in blue books), I encourage them to look up the articles to determine the correct answers to the questions.

In general, the different assessment measures are highly correlated. Most students who do well in the course do well on all of them. Some students are very anxious during examinations, and

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<th>Table 6. Problem from Final Examination.</th>
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A variety of experiments have established a distinction between short term memory and long term memory. Some investigators have hypothesized that formation of short term memories is a crucial prerequisite for the formation of long term memories. This hypothesis was examined in a study by Emptage and Carew, and some of the results of that study are shown in the Figure below.

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<th>A</th>
<th>Baseline (ASW)</th>
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<table>
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<tr>
<th>B</th>
<th>Baseline (CYP)</th>
<th>Short term</th>
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<td>SN</td>
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Figure abbreviations: MN: motor neuron, SN: sensory neuron, ASW: artificial seawater (control solution); 5HT: serotonin; CYP: cypromeptadine, a serotonin antagonist; all experiments were performed in the intact nervous system.

a. (5 points) What is the effect of serotonin on the amplitude of the motor neuron EPSP in part A of the Figure? Is the effect significant? What is the effect of serotonin on the amplitude of the motor neuron EPSP in part B of the Figure? Is the effect significant? How does part A differ from part B?

b. (10 points) Is the formation of a short term change in synaptic efficacy obligatory for the formation of a long term change in this experimental system? Explain. Propose one additional experiment to test this hypothesis in this experimental system.

c. (15 points) In another part of this study, the investigators were able to demonstrate that bathing the cell body in serotonin induced a long term change in synaptic efficacy, but no short term change, whereas bathing the synapses in serotonin induced a short term change in synaptic efficacy, but no long term change. Propose a mechanism to explain these results, and an experiment to test your hypothesis.

[Emptage and Carew, Science, 262:253 - 256, 1993]
do more poorly on the midterm and final than they do on the problem sets or term paper. Some students work better under pressure, and do better on the midterm and the final than they do on the term paper or the problem sets, which they may fail to turn in on time or to complete. Students who have difficulty with mathematical manipulations may do better on the final than on the midterm. On the whole, however, these different instruments provide a reasonably balanced and accurate view of a student’s mastery of the material in the course.

Discussion

Once I began to teach, I found myself repeatedly asking “How do I know whether a student has learned what I have taught?” A parrot can repeat meaningless phrases back to its trainer with high fidelity, but this does not imply understanding. A better indication of understanding is that one can use information that one has learned to solve novel problems. The other question I asked myself was: “What should students still remember about this course in a year, or in ten years?” In thinking back over the courses I had taken, I recalled teachers whose enthusiasm had gotten me excited about the subject matter, teachers who had taken a personal interest in me and had encouraged my creativity, and teachers who had challenged me to think critically about my work in their course. In contrast, many of the specific facts I had learned, especially in Biology courses, had to be unlearned or modified, since so much has changed over the last few years. These considerations impelled me to introduce the changes that I have described above.

There are several aspects of the course that may make it hard to apply to other courses. First, the course is an elective. Thus, if students do not like the emphasis on critical thinking, they can choose to drop the course and take other electives. At CWRU, Drop/Add does not end until the second week of the semester. A few students do drop the course, but several others often add it during the same period. In contrast, if a course is a requirement for a major, and demands critical thinking, then students will not be able to avoid it. This suggests that emphasizing critical thinking in core courses requires a commitment on the level of both the instructor and the Chair of the Department. This also suggests the need for systemic reform if critical thinking is to become part of the entire curriculum. If students do not have regular practice in using this skill in multiple contexts, they will tend to forget it.

Second, the course is designed for upper level undergraduates and beginning graduate students. It is possible to argue that students are more likely to be able to engage in critical thinking if they have a solid background of material, and are sufficiently mature. I would disagree with this viewpoint, however, because I observe that material is poorly retained, and I believe that the ability to think critically would help students retain the material better, as it would aid their ability to assimilate it and synthesize it with their prior knowledge.

Third, the class is relatively small, ranging in size from 12 to 30 students over the last seven years. The size facilitates discussion, and learning all of the student’s names. However, recent studies have shown that one can encourage discussion and small group work even in large lecture courses (McKeachie, 1986; White, in press). The small size of the course also makes it more feasible to administer assessments that involve essays. With large class sizes, multiple choice exams become much more attractive to an instructor because they can be graded more quickly. It may be possible to design multiple choice questions that encourage critical thinking, and grade a subset of these questions during the semester (Allen and Stroup, 1993). At some universities, an instructor may get help from upper level undergraduates and graduate students in grading questions that involve essays.

Fourth, I give two-thirds of the lectures in the course. This provides me with a great deal of flexibility that is much harder to obtain in a team-taught course. For example, if I do not cover all the material I wished to in one lecture, I can continue and finish it in the next lecture. Since a third of the course is taught by guest lecturers from several different Departments, I do need to deal with integrating very different teaching styles with my own. I explain to the guest lecturers how I encourage critical thinking, and sit in on their lectures, so that I can integrate the material they present into my own subsequent lectures in the course.

Teaching a course that encourages critical thinking is in some ways harder than teaching a more traditional lecture course. Questions from students may reveal the limitations of the instructor’s knowledge. Asking questions of the students that do not require a single right answer, but also
do not lead the discussion astray, requires skill and practice. Selecting key pieces of data to share with the students may require reading that goes beyond the textbook. Assigning readings becomes more difficult as well, since much of the material is in the technical literature, and may not yet have found its way into the textbook. The instructor must also deal with the tension between "covering the material" and insuring that students have actually incorporated the material into their own thinking. Finally, I can recall undergraduate lecture courses that were exciting, entertaining, and inspiring, and were associated with recitation sections in which discussions led by graduate students allowed students to explore the material in greater depth. Thus, traditional lecture courses may be of great value, if they are taught by truly gifted lecturers.

Being a student in a course that encourages critical thinking is also harder. One's lack of understanding is more likely to be publicly exposed, and the material may be presented in a less linear and logical way than it is in a good lecture. If one is used to memorizing material, or problem templates, it creates a great deal of anxiety to have to master another set of skills in order to do well in a course. Students also tend to be less interested in what other students have to say during discussion, because they believe that the only source of useful information is the professor. Sometimes they are correct; but a course that encourages group interactions can also encourage students to study together and work problems together. This is, in general, a more effective strategy for learning material, as long as each student contributes his or her share to the effort.

Students' ability to master the skill of critical thinking varies greatly. Some students are already able to do it when they take the course, and find it a pleasure to be in a course that rewards this skill. Still others find it anxiety-provoking to be asked to do it, but begin to feel a sense of mastery by the end of the semester. Some students cannot master the skill at all by the end of the semester, either from lack of appropriate prior experience, their stage of cognitive development, or their learning styles. Adjusting to these differences will require additional work. I hope to foster more inquiry-based approaches to allow students to construct their own understanding of the material, especially in the problem sessions (Hammer, 1995), and this may help to deal with these individual differences.

It is difficult to objectively assess the value of a particular educational approach. In general, it is not feasible to randomly divide students into two equivalent class sections, matched by gender, background, grade point average, and so on, and teach one class using a traditional lecture format, while teaching the other class using the approaches described above. Thus, in thinking critically about critical thinking, it is hard to assert definitively that it is superior to traditional approaches. Though the course that I teach has consistently had very positive evaluations from students over the years, it could be due to my enthusiasm for the subject, or the time I spend with students, and not to the critical thinking aspects of the course. Over the years, a variety of students have commented that the course had a major impact on their way of thinking, and some have claimed that it influenced their choice of careers, and encouraged them to go into the neurosciences. Again, this may reflect aspects of my personality as a teacher, and not my insistence on critical thinking skills.

Despite these caveats, I believe that critical thinking is an important and useful skill that should be introduced into a variety of science courses. My enthusiasm for these skills comes from my experience as a scientist. I have to think critically all the time. Moreover, I find that people who have these skills in many other fields, even nonacademic fields, often do better than those that do not. Reform efforts in the field of mathematics have focussed on critical thinking as essential (Curriculum 1989), as have more recent attempts to establish standards for science education (Benchmarks 1993). It is interesting that a co-founder of the Princeton Review, Adam Robinson, who has advised a very large number of students about studying for standardized tests, has recently published a book that, in essence, encourages students to think critically, asking questions about what they are learning, relating it to other things they know, "boiling it down" to key ideas, and forging connections with other subjects (Robinson 1993). My experience also suggests that students who do master these skills feel a real sense of accomplishment, and have much greater enthusiasm for research, and for science in general.
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Literature Cited


