



Unlocking Critical Thinking With Minor Course Modifications: Experiences in an Upper- Level STEM Course

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Background: Why Did I Try Teaching CT?

- I am professor in the Department of Chemistry, and I attended the 2017 Critical Thinking Faculty Institute after colleagues in my department recommended it
- I was warned that the workshop may not have many examples of critical thinking course development within the context of large lecture classes or for courses with a science, technology, engineering, or math (STEM) focus
- The workshop I attended had several presentations about how to apply critical thinking in STEM and larger lecture classes (as does this one!)
- It has been great to see the development of critical thinking courses here at Clemson, and the generally positive reception that my students have to critical thinking in my courses

BUT as the workshop progressed, I was not sure how I should specifically alter my course and syllabus to bring out critical thinking and still teach the topical material I wanted to cover



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My Example Upper-Level STEM Course: Bioinorganic Chemistry

- The course I decided to try modifying first was an upper-level Bioinorganic Chemistry course (CH4040/6040) – it has few prerequisites and a smaller (~25 student) enrollment
- I had taught this course several times and was comfortable with the material and flow before I modified the syllabus to explicitly incorporate critical thinking
- I realized from attending the Critical Thinking Faculty Institute that I was already teaching the course from a critical thinking perspective – as is common for more advanced STEM courses
- Because I wasn't sure how to change this course, I decided to take a minimalist approach and change very little at first – I could always do more later

It still seemed like a lot of changes:

- Expectations in syllabus
- CT assessments (pre- and post-tests)
- Presenting critical thinking
- Modifying how I taught topics
- Modifying problem sets
- Modifying exams



My Reservations and Goals

Initially, I was quite hesitant about the jump to formally teaching a critical thinking course because:

- I really wanted to focus on teaching the scientific topics – especially since I already act as a “facilitator/translator” from chemistry to biology and back
- I didn’t want to make it into a discussion- or project-based course
- I didn’t want to increase the learning, teaching, or grading burdens, and I have had inconsistent results from peer-led or peer-reviewed assignments
- I am not a critical thinking expert

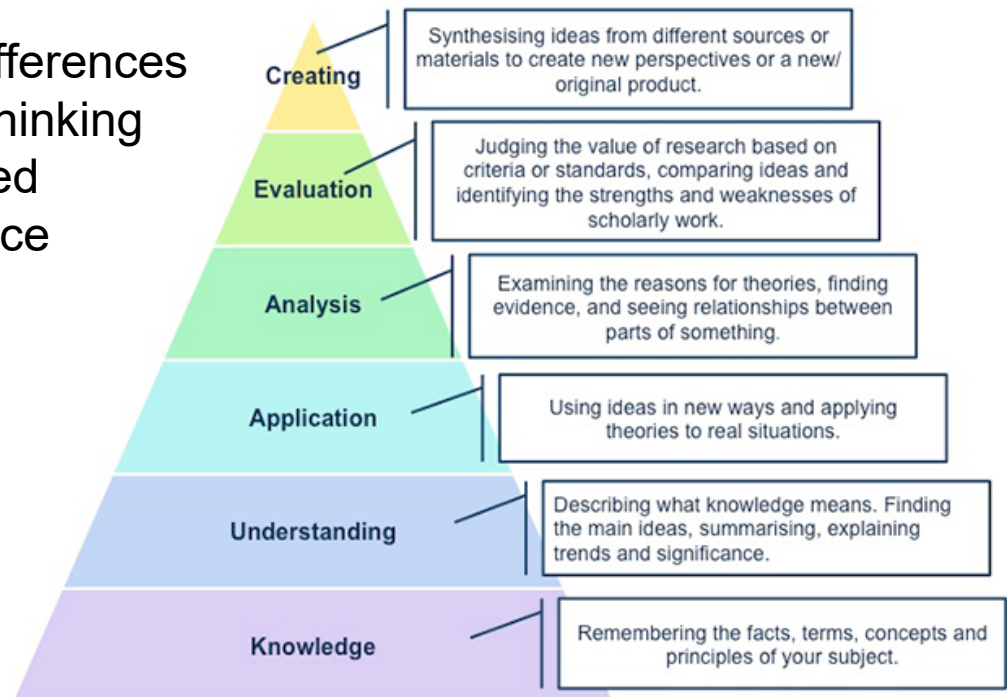
I overcame most of these reservations and met most of my goals by focusing on how scientists use critical thinking



Setting Critical Thinking Expectations

- In the syllabus, added a critical thinking section that defined critical thinking and explained that this was a critical practice in science
- In the syllabus and in the first class, emphasized that critical thinking is a skill that employers, graduate schools, and pre-professional schools are looking for in graduating science majors
- In the first class, explained the differences between critical and non-critical thinking and why critical thinking is required for the unbiased practice of science
- In assigning the first problem set, explained Bloom's taxonomy

Emphasized that critical thinking takes practice, that everyone is at different levels, and that there are limitations to being able to think critically



Course Outline Changes

- The course introduction was shortened to allow time to define critical thinking in science and its benefits
- One content class was replaced with a class devoted to critical thinking in science (at the end of review)
- The problem sets and exams were modified
- The full syllabus with all the critical thinking changes highlighted in red is provided in Box

Date	Topic	Reading	Assignments due*
12 Jan. (Th)	Introduction and critical thinking overview		
17 Jan. (T)	Inorganic chemistry review	Chapters 1 & 2	Critical thinking pre-assessment (online)
19 Jan. (Th)	Inorganic chemistry review		
24 Jan. (T)	Biochemistry review	Chapter 3	Problem set 1
26 Jan. (Th)	Biochemistry review		
31 Jan. (T)	Physical methods	Chapter 4	Problem set 2
2 Feb. (Th)	Physical methods and timescales		
7 Feb. (T)	Critical thinking: Why and how?		Problem set 3
9 Feb. (Th)	Metal uptake / transport / storage	Chapter 5	
14 Feb. (T)	Metal uptake / transport / storage		
16 Feb. (Th)	Metal uptake / transport / storage	Chapter 6	
21 Feb. (T)	Metal uptake / transport / storage		Problem set 4
23 Feb. (Th)	Metal uptake / transport / storage	Chapter 7.1, 8.1, 8.2	
28 Feb. (T)	Review		
2 Mar. (Th)	MIDTERM EXAM		
7 Mar. (T)	Metals in proteins	Chapter 9	
9 Mar. (Th)	Metals in proteins	Chapter 10	
14 Mar. (T)	Metals in proteins		Problem set 5
16 Mar. (Th)	Metals in proteins	Chapter 11	Paper outline approved*
20-24 Mar.	Spring break		
28 Mar. (T)	Metals in proteins		
30 Mar. (Th)	Metals in proteins	Chapter 12	
4 Apr. (T)	Metals in proteins		Problem set 6
6 Apr. (Th)	Metals and nucleic acids	Chapter 7.2-7.4	Paper due for review*
11 Apr. (T)	Metals and nucleic acids	Chapter 8.3-8.4	
13 Apr. (Th)	Metal toxicity	Outside reading	Problem set 7
18 Apr. (T)	Metal toxicity		Peer review due*
20 Apr. (Th)	Metals in medicine	Chapter 13	Critical thinking post-assessment (online)
25 Apr. (T)	Metals in medicine		Problem set 8
27 Apr. (Th)	Review		Revised paper due*
3 Apr. (W)	FINAL EXAM 3:00 – 5:30 pm (100 Earle)		

Critical Thinking Resources: CT²

To introduce critical thinking to the class, I adapted sections from the slides in the Critical Thinking Faculty Institute workshop

- Explained on how critical thinking applies to the teaching and practice of science
- Focused on the disconnect between the top-down method of teaching science and the bottom-up practice of science
- Provided examples of critical thinking definitions and frameworks as well as critical thinking (or lack thereof) stages
- Provided a list of a few faulty methods of assumption checking and logical fallacies and explained how they related to bias in scientific experimental design and in scientific publication

Since I only covered the general basics and then focused on how critical thinking applies to science, I didn't have to be an expert

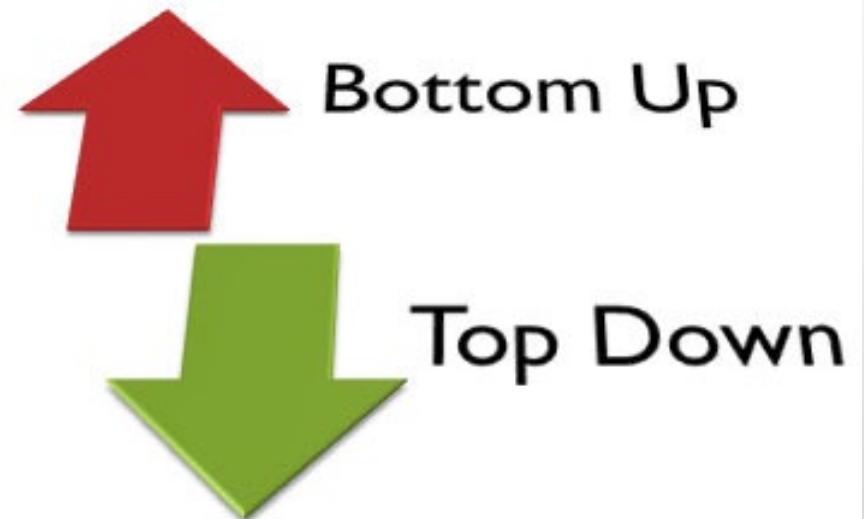
Critical Thinking and Science

Science practice is bottom → top

- Scientists trying experiments and making observations
- Observations are generalized into hypotheses
- Hypotheses become theorems and laws if they withstand many different observations/experiments/challenges

Science teaching is often top → down

- Here's this law, here's this rule, here's when to apply them
- Emphasis on memorization
- At this level, science teaching has no critical thinking



A Disconnect between Science Learning and Practice

Science practice

- I have a question and imperfect tools to probe the problem
- A given tool (instrument or experiment) may or may not illuminate the path to the answer
- A tool may partly answer the question but reveal additional problems or questions that need other tools to address

Teaching of science: often everything is linear, known, and right or wrong

Practice of science: try different ways of looking at a problem; each may or may not help you understand the situation more

Reality of science learning

- Multiple answers have various degrees of correctness; rarely as simple as “true” or “false”
- Very difficult to operate as “least correct” and “most correct”
- Error-checking (does 20 molar sound right?) and order of magnitude estimates (do I need 0.01 g or 100 g of this reagent?) are vital skills

Evaluation of student learning in science

- Often simple multiple-choice and true false (especially in beginning or large classes)
- “Plug and chug” into equations

Why Is Critical Thinking Difficult?

- Because it's often hard for us to see our own assumptions without some kind of outside assistance
- Because we don't want to question assumptions – life becomes more difficult and even uncomfortable
- Because young adults especially are also grappling with intellectual development
- Because people sometimes do not have the bandwidth to do it



Faulty Assumption Checking and Logical Fallacies: The Bane of Critical Thinking

Incorrect checking of assumptions

- Assumption is accurate because it is **corroborated by my peers** (groupthink)
- Assumption is accurate because it is **corroborated by experts** (dependence on authority as *de facto* correct); leads to false equivalence of experts
- Assumption is accurate because it is **corroborated by my own experience** (self-delusion, denial, and blind spots; “anecdotal”); leads to naturalistic and faith-based fallacies
- Assumption is accurate because **I have tested it out** (flawed problem posing)

Common logical fallacies in science

- *Affirming the consequent*: seeking evidence or choosing techniques to confirm a hypothesis rather than to disprove it
- *False analogy*: assuming that outcomes will be the same in similar systems (e.g., cells vs. animals or mice vs. humans)
- *Confirmation/publication bias*: favoring and/or publishing only data that supports hypotheses; publishing positive findings rather than null or contradictory results

Changes to Problem Sets and Exams

- **Problem sets were increased by one critical thinking question each** (to 6 total)
 - Early problem sets focused on identifying the levels of thinking required to answer a problem
 - Later problem sets included short scientific articles that students were asked to analyze for the science AND for the critical thinking in coming up with the idea, designing the experiments, or evaluating the conclusions
- **Midterm and final exams included two critical thinking questions**
 - One was focused on giving examples of critical thinking in science
 - A bonus question was used to assess students' opinions about the critical thinking component of the course or how they had applied critical thinking
- Resulted in somewhat longer problem sets to finish and grade, but not much longer
- Gave students a new perspective on why and how they were learning – and me insight into how students were thinking
- Could pass the class without demonstrating much critical thinking, but couldn't be a top student



Examples of CT Problem Set Questions

- **Problem set 1**

For questions 1-5, assign each question to a particular stage of critical thinking using Bloom's taxonomy diagram below and justify your assignment.

- **Problem set 2**

Write one question – and its answer – on the biochemistry review section of the course that requires thinking at the application level or higher on the Bloom's taxonomy diagram. Give the Bloom's taxonomy level for your question and justify this assignment.

- **Problem set 4 (after critical thinking presentation)**

List the three commonalities among the different critical thinking frameworks and discuss how each applies to critical thinking (i.e., why are these three traits always present in different frameworks of critical thinking?).

- **Problem set 5 (after answering other questions about the same article)**

The authors compare Na^+ efflux results obtained using their oligoamide macrocycles with those of gramicidin and valinomycin. Using your critical thinking skills, explain what this comparison was designed to test and how the authors' interpreted their results. Do you agree with this experimental design and the authors' assumptions? Why or why not?

Examples of CT Problem Set Questions

- **Problem set 6 (after answering other questions about the same article)**
Explain the critical thinking process the authors describe in the introduction that led to the experiments and conclusions presented in this paper. What previous assumptions did the authors question?
- **Problem set 7 (after answering other questions about the same article)**
From a critical thinking standpoint, is the significant advance reported in this paper truly significant? Give at least two reasons why AND two reasons why not.
- **Problem set 8**
Explain the importance of critical thinking in science and give three specific examples from this course of how critical thinking was demonstrated (either by you or others) to improve science practice or literacy.
- The progression of critical thinking questions from identification to application helped students think more critically about the course material (including critical thinking) and how and why it was presented
- While some students needed significant adjustment to the idea of critical thinking, others found it useful to have critical thinking explicitly covered and expected

Examples of CT Exam Questions

- **Midterm question 1**

Give a specific example of how critical thinking is vital to the unbiased practice of science.

- **Midterm bonus question**

Indicate whether you have found the critical thinking component of this course useful and briefly state why or why not.

- **Final exam question 1**

List two different components of critical thinking and explain how each one is vital to the unbiased practice of science.

- **Final exam bonus question**

How useful have you found the critical thinking component of this course as it relates to science (i.e., scientific exploration, assumptions, and/or bias)? Briefly explain.

The critical thinking questions for this course comprised approximately 15% of the overall grade

Assessing the Impact of Critical Thinking in My Bioinorganic Course

I taught essentially the same course with the same problem sets and the same exams in 2017 and in 2018 with the critical thinking component added

Evaluation Question	Mean 2017 (n = 14; 100%)	Mean 2018 (n = 12; 100%)
G1. The instructor clearly communicated what ...	4.43	5.00
G2. The instructor made the relevance of the ...	4.71	5.00
G3. The course was well organized.	4.86	5.00
G5. The instructor's teaching methods h ...	4.36	4.89
G7. The instructor clearly explained what was ...	4.29	4.78
G8. The instructor kept me informed about my ...	4.62	4.78
G9. The feedback I received on assignments ...	4.64	5.00
G10. Overall, the instructor is an effective ...	4.64	5.00
D5. Applying knowledge to solve real-world ...	4.64	5.00
D6. Thinking through arguments or problems.	4.21	5.00
D7. Evaluating ideas scientifically.	4.46	5.00

Student Comments about Critical Thinking

- **Comments from evaluations:**

“The homework, as much as I hated how time consuming it was, was actually very useful and helped develop critical thinking skills that I had never developed in my other classes.”

“Also, giving out homework as problem sets that made you think motivated me to try and do my best on each and every one.”

“critical thinking problems were good. helped me think about thinking”

- **General feedback:**

- About 10-15% of students in the class do not engage well with the critical thinking aspects, but they understand and admit this
- Students have mentioned that the critical thinking skills developed in this course help them with other courses too
- Students have mentioned that they feel more capable of becoming practicing scientists after focusing on scientific critical thinking

Adapting a “traditional” STEM course to incorporate critical thinking can be straightforward and effective

Acknowledgements

- **Clemson CT² Faculty Institute and David Knox**
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- **Students in CH8070 (my graduate-level inorganic chemistry critical thinking course)**

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