AC 2008-544: EMPLOYING SOCRATIC PEDAGOGY TO IMPROVE ENGINEERING STUDENTS' CRITICAL REASONING SKILLS: TEACHING BY ASKING INSTEAD OF BY TELLING

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Employing Socratic Pedagogy to Improve Engineering Students' Critical Reasoning Skills: Teaching by Asking Instead of by Telling

Abstract

Engineering faculty agree almost universally that the development of students' higher-order intellectual or cognitive abilities is one of the most important educational tasks of engineering programs. These abilities underpin our students' perceptions of the world and the consequent decisions they make. Specifically, critical thinking (critical intelligence) – the capacity to probe and evaluate skillfully, analytically and fairly the quality of evidence, formulas, precepts and pieces of received wisdom that too often go unexamined and unchallenged and detect inaccuracies, error, hypocrisy, manipulation, dissembling, and bias – is central to both personal success and national needs. This paper assumes that the capacity of undergraduate engineering students to learn to apply good reasoning to problem solutions can be nurtured and developed by an educational process aimed directly at developing students' critical thinking skills.

More specifically, the paper reports on the judicious and amiable use of the Socratic Method of teaching by systematic questioning – instead of teaching by telling – to emphasize and foster critical reasoning skills in electrical engineering, computer engineering and engineering physics undergraduate students at the University of the Pacific (Stockton, California). The selective, careful use of the Socratic Method (in combination with traditional lectures and active learning exercises) in electrical circuits, linear systems, signal processing, probability and statistics, electronic communications, and senior capstone design project courses, teaching laboratories and projects helped improve student participation, got the students actively involved and excited about the projects and the material being taught, motivated the students to better master course content and taught the students to learn to think and reason more clearly, accurately, relevantly, logically, rationally, ethically and responsibly.

This paper discusses how the judicious, sensible and affable use of the Socratic Method in the aforementioned educational settings facilitated the development of students who are learning to possess the basic skills of thought and reasoning such as the ability to: identify, formulate and clarify questions; gather relevant data; identify key assumptions; identify the sources of the data and assumptions, and evaluate the relevancy and accuracy of the data and assumptions; identify and trace significant implications of the data and assumptions; consider alternative explanations without distortion or self-deception; and reason to logical, rational, responsible and ethical conclusions and decisions.

The Socratic Method does not always work in all contexts nor for all students, but it can be effective for most students most of the time. The paper discusses how the Method was used to integrate questioning and learning in the aforementioned courses, laboratories and projects to stimulate and challenge students, to assist them to acquire knowledge, and to help students discipline their mind by developing intellectual skills and traits of mind such as intellectual acuity, intellectual honesty, intellectual humility, intellectual

perseverance, intellectual autonomy, intellectual empathy, intellectual integrity and intellectual responsibility. These skills and traits plant the seeds to help prepare students to: (a) become practicing professionals who are fair-minded, who have confidence in reason and who are undaunted when faced with the need to master new technologies; (b) become scholars undertaking advanced study; (c) take ownership of new ideas and modes of reflective thinking and reasoning; and (d) be prepared and motivated to develop into life-long self-directed and independent, yet collaborative, learners who possess an improved ability to speak, write and listen and the mental discipline needed to apply sound judgment and problem-solving skills to novel problems.

Motivation for Using the Socratic Questioning and Some Specific Techniques for Implementing the Socratic Method

Teaching occurs not just through imparting information but also through arousing intellectual passions and enthusiastically presenting an example of thought in action. All knowledge, like all education, is ultimately driven by the questions asked. As engineering educators, one of our tasks is to pose the right questions, and help students to learn to ask the right questions and to learn to formulate reasoned answers. These are relatively difficult teaching goals. This paper proposes that it may be possible to accomplish these goals by combining the use of traditional lectures with active and collaborative learning and with the Socratic Method of directive questioning/reasoning, in which the instructor poses a problem and asks a series of directive, probing questions, to help students follow a particular approach to solving the problem.

The directed questions contain useful information to assist students in (a) understanding the problem, (b) devising a plan to solve the problem, (c) carrying out the plan, and, finally, (d) reviewing/extending the problem. In the last step [step (d)], students are encouraged to reflect and look back at the implications of the problem solution, what the student has done, what worked and what didn't, to enable the student to better understand the outcome of the problem solution and to predict what strategy to use to solve future problems, if these relate to the original problem. Throughout the entire process [steps (a) through (d)], if the student gets "stuck," the instructor may supply a hint. The result is an effective, lively give-and-take dialog with students that fosters a process of progressively sharpened understanding, helping students reason their way to the problem solution or to greater intuitive understanding of basic and advanced engineering, physical and mathematical concepts.

The first author of this paper generally presents material in class as a balance between a traditional lecture style, using overhead transparencies together with providing students with detailed handouts containing factual material (such as lengthy mathematical derivations, complicated drawings/plots or a large number of seemingly unrelated facts). Copies of the handouts are provided to the students well in advance of the class meeting. The notes are highly detailed but also cryptic enough that they don't serve as a substitute for attending lecture. The notes significantly lessen (but not eliminate) students' writing burden: students annotate the handouts during lecture, but they do not have to write constantly and frantically at the expense of comprehending. This frees up the students' and the instructor's time for asking questions, thinking about the answers, formulating and articulating answers, refining the answers, clarifying key points of physical principles and mathematical expressions and equations, listening to and learning from each other, developing intuitive and physical insights and mathematical skills, improving understanding and solving example problems from modern engineering practice.

The classical lecture format has its advantages, but its main disadvantage is that if the instructor is doing almost all the talking, it is difficult to gauge students' understanding of the material. Watching students' faces (glazed looks spread across the class when the instructor may or may not be making sense) is not an accurate, reliable technique to provide useful information on the level of students' comprehension. This necessitates the need to try some other technique to obtain feedback from the class as to whether they are "getting it" and to adjust the lectures if they are not. The Socratic methods attempts to address that need by having students solve problems verbally in class with the aid of a directed line of questioning. When the students and the instructor collaboratively solve an example problem in lab or lecture, such as a mathematical derivation or a design problem, the instructor can set up the introduction to the problem and then require the students to orally carry out the remaining work involved in solving the problem, almost entirely on their own with almost no interference from the instructor.

One by one, each and every student is required to contribute to the step-by-step solution of the problem: the first student sitting in the first row in the classroom is asked to provide the initial listing of the goals and objectives of the problem, then the student sitting right behind the first student is asked to setup the first equation, then the student sitting right behind the second student is asked to continue the equation setup or to solve the equation that was set up by the prior student, and so on. Each student in turn supplies the next step in the design problem solution, or the next line of a computer program or the next step in the mathematical derivation. This way, the instructor can gauge immediately how much students understand. And the lecture is not progressing too fast for the students, since they supply all the answers.

Students work methodically and collaboratively through all the various steps of the problem solution, culminating in a sanity check of the final result. This problem solution process creates a more playful, and simultaneously more intellectually charged atmosphere in the classroom. Throughout the process, there is minimal involvement on the teacher's part, except to provide hints and to ask the students directed questions to help them make progress if they are "stuck." Students are also encouraged to ask questions if they are "stuck" or if they are confused.

Specific Examples of Socratic Questioning

The following are example transcripts of portions of teaching sessions using the Socratic Method in undergraduate engineering courses at the University of the Pacific.

Example 1. Example transcript of a portion of a teaching session, using the Socratic Method, in an Analog and Digital Communications Systems senior elective course. The class is taught in Spring 2008 and a total of 4 students are enrolled: Bryan, Justin, Jesse and Patrick.

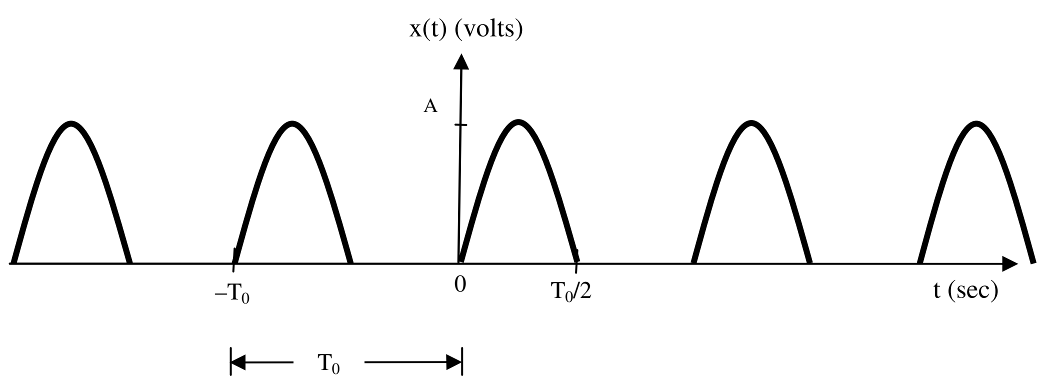
Professor (MG): Is it important to discuss the idea of the size of a communication signal? If yes, why? What is this idea useful for? If not, why? Bryan, please go first.
Bryan: Yes, it is useful, because you need to know how large a communications signal should be so that it will reach its destination, for example in a cellular phone system you want to design a signal that is large enough that it will be able to propagate from your cell phone and be received by the cell phone tower, and from one tower other towers in the network of towers.
MG: Good. That is correct. Justin, do you have anything to add to this?
Justin: Yes, we want the signal to be large enough, but we should also make sure that the signal is not too large, so that it will not interfere with other cell phone users and overwhelm their signals. So you want to design the signal so it is large enough but not too large, not larger than is necessary.
MG: Good. Jesse, can you suggest a method to measure the size of a signal.
Jesse: Um … not sure.
MG: Think back to your first Freshman calculus class. Can you suggest some mathematical quantity from your Calc I class that is a single number that could indicate the signal size, one number that will capture the signal strength?
Jesse: The derivative of a signal … no, wait, that would not be very good. How about the area under the signal?
MG: Good suggestion. Let’s consider the area under the signal. Now, Patrick, do you think the area is a good measure of the signal strength?
Patrick: Um …. Yes, I don’t see why not.
MG: What would be the advantage of using the area?
Patrick: It is easy to calculate. You just acquire the signal, sample it and run it through software to calculate the area, like Matlab or Labview. Pretty easy to do.
MG: Right. Now what would be a disadvantage, if any, of using the area under the signal?
Patrick: Not sure.
MG: OK. Bryan, back to you. What do you think?
Bryan: The area is not good, because your signal could be for example a strong periodic sinusoid with large amplitude swings but when you take the area under the signal it is zero, or close to zero.
MG: Why?
Bryan: Because you have as much positive area above the horizontal time axis as you do below the axis, and they cancel each other out.
(Jesse and Patrick nod their heads in agreement.)
MG: Good. So I think we can agree that the area is not a good measure of the size of a signal. Justin, your turn. Can you suggest something better?
Justin: How about the area under the square of the signal?
MG: Jesse, is Justin’s idea a good idea? Why?
Jesse: Yes, because the area under the square of the signal is always positive and it solves the problem of positive and negative area cancellations.

MG: That's correct. Patrick, I want to write down the mathematical expression for the area under the square of the signal. Help me out.
Patrick: The integral from minus infinity to infinity of the signal squared.
MG: Integral with respect to what? What is the variable of integration?
Patrick: Um … time, t.
MG: (Writes the following equation on an overhead transparency): $E_g = \int_{-\infty}^{\infty} |g(t)|^2 dt$
Bryan: I think you have a mistake. We don't need the absolute value signs because we are squaring the signal.
MG: Justin, do you agree or disagree with Bryan?
Justin: Disagree.
MG: Why?
Justin: Because obviously you must have had a good reason to put the absolute value bars in there … (everybody laughs).
MG: Jesse, care to comment?
Jesse: If the signal is complex it makes more sense to first take the absolute value and then take the square. If the signal is real then taking the absolute value before the square will make no difference. So this equation is more general.
MG: Exactly.

Example 2. Example transcript of a portion of a teaching session, using the Socratic Method, in the Systems and Signals Analysis junior-level required course. The class was offered in Fall 2007 and has, on average, about 15 students per class.

In this example, we begin the transcript at the point in time after the students and the instructor have previously worked together to analyze (that is, find the Fourier series representation for) the half-wave rectified sinusoidal waveform pictured below. The half-wave rectified sinusoid is used in practical DC power supplies and other practical circuits. The waveform is a periodic signal with period T_0 and is given by

- $x(t) = A \sin(2 \pi t / T_0)$, if $0 \leq t < (T_0 / 2)$
- $x(t) = 0$, if $(T_0 / 2) \leq t < T_0$



Assume that the instructor and the students have previously shown in class that:

- The Fourier coefficient a_0, i.e., the average (DC) value, is $a_0 = A / \pi$
- The Fourier coefficient $a_1 = -A / 4\pi$.

- The remaining Fourier coefficients a_k, for $k \neq 0$ and $k \neq 1$, are equal to
  - $a_k = -A / [\pi (k^2 - 1)]$, if k is even, i.e., if $k \in \{\ldots, -4, -2, 2, 4, 6, 8, \ldots\}$
  - $a_k = 0$, if k is odd

Professor (MG): [Poses the following question to the students]: Now that we have analyzed the half wave rectified sinusoid x(t) from the last example, we want to do the "opposite" operation, that is, let's synthesize -- in other words, design, create, construct -- the signal x(t) as a sum of <u>real</u> sinusoids.
MG: (Calls on the first student): Haitham, let's write down the general Fourier synthesis equation for any periodic signal x(t). Please tell me what to write down.
Haitham (tells MG what to write, and MG writes it down on an overhead transparency):

$$x(t) = \sum_{k=-\infty}^{\infty} a_k \exp(j\ [2\pi / T_0]\ k\ t)$$

MG: Casey, customize the Fourier series synthesis equation based on what we know about the half-wave rectified sinusoid.
Casey: $x(t) = a_0 + a_1 \exp(j\ [2\pi / T_0]\ 1\ t) + a_{-1} \exp(j\ [2\pi / T_0]\ (-1)\ t) +$

$$\sum_{k=-\infty}^{\infty} a_k \exp(j\ [2\pi / T_0]\ k\ t),$$ with $k \neq 0$ and $k \neq \pm 1$ and k equal even integers only.

(MG writes the equation down on an overhead transparency.)
MG: Brandon, plug-in the Fourier series coefficients for our signal.
Brandon: $x(t) = (A / \pi) + (-A / 4\pi) \exp(j\ [2\pi / T_0]\ t) + (-A / 4\pi) \exp(-j\ [2\pi / T_0]\ t)$

$$+ \sum_{k=-\infty}^{\infty} (A / [\pi (1 - k^2)]) \exp(j\ [2\pi / T_0]\ k\ t),$$ with $k \neq 0$ and $k \neq \pm 1$ and k equal to even integers only.

MG: Travis, please continue.
Travis: $x(t) = (A / \pi) + (-A / 2\pi) \cos([2\pi / T_0]\ t) +$

$$\sum_{k=-\infty}^{\infty} (A / [\pi (1 - k^2)]) \exp(j\ [2\pi / T_0]\ k\ t),$$ with $k \neq 0$ and $k \neq \pm 1$ and k equal to even integers only.

MG: Kimo, we want to rewrite the sum as the sum of real sinusoids only. What is the first thing we need to do?
Kimo: (Takes a minute or so to think the question over) -- We need to have the second half of Euler's equation in the sum … So we can write out the terms in the sum, then use Euler's to add up the terms with positive and negative frequencies. This will give you real sinusoids in the sum.
MG: Good. Xuan, go ahead and do that.
Xuan: We can do that by having the sum run on positive index values only.
MG: Good. Go ahead and tell me what to write.
Xuan: $x(t) = (A / \pi) + (-A / 2\pi) \cos([2\pi / T_0]\ t) +$

$$\sum_{k=2}^{\infty} (A / [\pi(1-k^2)]) [\exp(j\ [2\pi/T_0]k\ t) + \exp(-j\ [2\pi/T_0]k\ t)]$$

MG: Xuan, are you forgetting something?

Xuan: Um … not sure.
MG: How about the index on the sum? Does the sum hold for all k?
Xuan: Oh … only for k even.
MG: Good job, Xuan. Now I'm going to multiply the numerator and denominator in the sum by 2, to make it easier to see Euler's equation:

$$x(t) = (A / \pi) + (-A / 2\pi) \cos([2 \pi / T_0] t) + \sum_{k=2}^{\infty} (2A / [\pi(1-k^2)]) [\exp(j [2\pi/T_0]k t) + \exp(-j [2\pi/T_0]k t)] / 2, \quad k \text{ even.}$$

MG: Robert, what's the last step?
Robert: $x(t) = (A / \pi) + (-A / 2\pi) \cos(2 \pi f_0 t) +$

$$\sum_{k=2}^{\infty} (2A / [\pi (1 - k^2)]) \cos(2 \pi f_0 k t), \quad \text{for k even (eq. 3.99)}$$

MG: Eq. (3.99) synthesizes the half wave rectified sinusoid x(t) as a sum of <u>real</u> sinusoids. (At this point it is a good idea to follow these mathematical derivations by an interactive discussion, guided by a set of directed questions, on why it is important to synthesize signals from <u>real</u> component sinusoids as opposed to synthesizing from <u>complex</u> exponentials.)

Example 3. Example transcript of a portion of a required student class participation memo in the Systems and Signals Analysis course. The course lectures utilize the Socratic Method.

This required participation memo was submitted by Brandon, a bioengineering junior:

"My memo is based in part on the peer reviewed article that can be found at: http://hyper.ahajournals.org/cgi/content/full/25/6/1276.

In class the Professor mentioned that convolution y(t) = x(t) * h(t) can be applied to physiological systems, as well as to electrical and electronic systems, to take advantage of the concept of impulse response h(t) to derive the response y(t) of an LTI system to any input x(t) to the system. In class I asked how exactly the impulse response is determined for physiological systems. The Professor bounced the question back to the class and asked us to think about this question aloud together as a team with him. After some group discussion we agreed that system identification for a physiological system uses the same basic concepts as those we studied in class for measuring the impulse response of an electrical/electronic system, but that measuring h(t) for a physiological system is probably highly complicated because some physiological systems would change once you applied an impulse input to the system/organ.

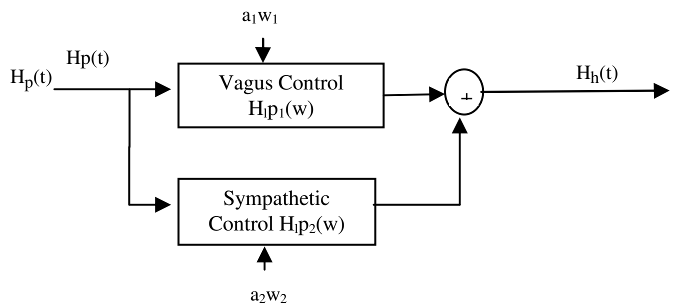
Being a bioengineering major our discussion in class has piqued my curiosity and after class I studied the aforementioned paper to try to learn more about this interesting problem. I found that measuring the impulse response of a physiological system is often more complicated than that of many electrical systems. This is mostly due to the fact that live human physiological responses are difficult (but not impossible) to measure and control, because in many cases of interest, when measuring the impulse response of a physiological system in the laboratory, there are many challenges: control of the physiological system is often indirect and incomplete, and measurements are often indirect, especially in terms of instantaneous lung volume, which is prone to some of the highest impulse response measurement errors due to its complicated measurement technique.

For example, several papers published by researchers investigating the subject of the measurement of the impulse response of a physiological system, appearing in the open literature, have the goal of determining the system impulse response of a closed loop cardiovascular system. This type of system is often modeled as having negative feedback, and rough models for the physiological systems are derived from general anatomy and physiology considerations. In the case of these experiments the response of the system changes depending on the activities of a patient, their individual health, and the medications given during the experiments. The impulse response in the case of these experiments is sometimes chosen to be the heart rate at a given time, which is derived from the EKG data. In some cases, this answers the question of how the system impulse response is measured for a live physiological system: the impulse response is measured by controlling some of the behaviors of the subject and measuring basal activity.

The impulse response measurement problem is exacerbated by the fact that often the physiological system under test changes with every minute movement of the physiological organ; that is, the system is dynamic and its properties change with time (i.e., the system is time varying). To remedy this problem of time-variance, the impulse response is measured repeatedly several times for each individual. Medications are sometimes given to the physiological system under test, to cause the system to change in a lab setting to help determine the impulse response characteristics under varying test conditions.

The concepts of systems analysis also apply to model cardiac rhythm. One of the most important things about the heart is its rhythm. If the heart is beating too slow, not enough nutrients and oxygen are being supplied to the body; in contrast, if the heart is beating too fast it is wasting energy, and given its size the heart already consumes an inordinate amount of nutrients compared to the other muscles.

The heart rate is regulated by several different mechanisms. The first mechanism is the heart alone: each region in the heart has its own pacemaker/rhythm. The other mechanisms come from the sympathetic and parasympathetic (the Vagus nerve) nervous system. As discussed in the article above, this can be represented as several different systems. The parasympathetic (Vagal) cardiac control operates as a low pass filter as well as the sympathetic control. These have different cutoff frequencies of 1 and .15 Hz respectively. Modeling these as low pass filters makes intuitive sense because the natural pacemakers in the heart are generally well above the resting heart rate. A block diagram modeling this is shown in the figure below.



In the figure, a_1w_1 and a_2w_2 are constants, where w_1 and w_2 are the cutoff frequencies and a_1 and a_2 are either zero or one depending on which system is active. $H_p(t)$ is the pacemaker heart rate and $H_h(t)$ is the modified heart rate that is actually executed."

<u>The first author's (i.e., MG's) comment on this example</u>: Students are required to write three course participation memos per semester (one memo about every five weeks) in each of the first author's courses. Each memo counts for 1% of the students' overall course grade. This example memo is not a typical course participation memo – it is longer and more in-depth than most. About 25% of all course participation memos submitted by students in the first author's classes may be classified as belonging in the same category of insightful, in-depth memos as this example. The first author has also required students to write class participation memos during his first three semesters of teaching, during which time Socratic questioning was not used in the first author's teaching, and none of the memos submitted for grading during that entire period of time were nearly as good as the top 25% of the memos submitted when Socratic questioning was used in the class.

Example 4. Example transcript of a portion of a student class participation memo in the Random Signals (applied probability and statistics) required senior-level course. The course lectures utilize the Socratic Method.

This required participation memo was submitted by Brian, a senior double-majoring in computer engineering and music performance:

"Asking questions can have great practical value. In fact most of the technical, economic and policy problems that face humanity, our society and country are intractable partly because we do not apply the methods associated with critical questioning to these problems. We overwhelm these problems with technical, numerical and empirical overkill and miss the most elementary deficiencies in our reasoning. Dealing with probability and statistics (random signals) teaches us to ask "What are the underlying assumptions structuring the inquiry being carried out here?" Inquiring into meaning is something that one must do in engineering- and scientific-based thinking and it is something that those of us with a technical and scientific training often forget to do.

My majors are computer engineering and music. I am sensitive to assumptions, axioms and definitions. From my experience as a student and from working two co-op terms (a total of 12 months) in industry I find that many engineers, scientists and other technically trained individuals (and business persons) tend to view assumptions, axioms and definitions as semantics or technicalities. But a good engineer, mathematician or a logician knows that if you can get someone to accept certain definitions and basic assumptions, you have won your argument before you have even initiated it. Thus a sensitivity to the nature of truth, the motivation behind questions and the assumptions underlying arguments is utterly critical.

Many engineers and scientists that I have worked with will accept some measurable quantity such as probabilities and statistics associated with IQ as a given. But someone with solid engineering or scientific training will ask what does IQ mean? Is it one thing or many? Who made up the questions used in measuring it? etc. As we now know all of these questions are of fundamental importance in thinking about IQ. Many would not question that IQ measures something but an inquiry into the meaning of the term using critical questioning would reveal the problems with the concept long before the scientific apparatus that is taking it out could be constructed.

We (the world in general and the US in particular) have huge problems in formulating foreign policy, in guaranteeing that our industries can respond to epistemological change, in anticipating what will be considered a problem when it was not seen as a problem in the past etc. All of these things can be approached with the methods of deep questioning. Our failure to grasp the importance of analyzing probabilities and statistics, ideas, differing viewpoints, justifications, opinions and accounts and, in the process, learn how to construct a logical assessment . . . and defend our conclusions with facts and lucid argument is literally costing us in lives, power, money, the environment and just about anything you can name."

<u>The first author's (i.e., MG's) comment on this example</u>: basically the same comments as those for the Systems and Signals Analysis student participation memo quoted above.

Assessment

Assessment of student learning when Socratic questioning was used in each of the aforementioned University of the Pacific engineering classes (Electric Circuits, Systems Analysis, Digital Signal Processing, Random Signals, Communications Systems and Senior Design Projects) at the end of each of the first author's last six semesters of teaching (Spring 2005 to Fall 2007, inclusive), compared to assessment of the first author's classes at Pacific when Socratic questioning was not used (Fall 2003 to Fall 2004, inclusive) shows that when the Socratic Method was used, students:

- Were generally considerably more actively, enthusiastically and productively engaged with the material, as evidenced by the fact that students:
    - Asked many more questions in class and lab, and asked many more challenging, perceptive, insightful, sophisticated questions (i.e., both the quantity and quality of questions improved)
    - Answered the instructor's questions with less trepidation and hesitation and with elevated levels of enthusiasm and confidence, demonstrating

higher levels of understanding, sophistication, intuition and insight into the material
  - Came to office hours considerably more frequently, stayed longer in the instructor's office, and asked more and more in-depth questions in office hours
  - Commented much more frequently and freely without almost any inhibitions on their student colleague's questions and remarks in class, lab and office hours, and provided more significant insights, corrections and interpretations to their colleague's remarks and better answers to colleague's questions
  - Provided more insightful and more in-depth interpretations and analysis of experimental and numerical results in design and computer assignments and laboratory exercises
  - Wrote course participation memos that were more carefully and thoroughly researched and were more exhaustive, complete, inclusive, comprehensive, extensive and in-depth
- Scored slightly higher, on average, on homework, lab, design and computer assignments and quizzes and examination grades, compared to the scores when Socratic questioning was not used. This is despite the fact that the assignments and exams are, on average, slightly to moderately more difficult and challenging in the Socratic-based courses than they were in the non-Socratic based classes. (The scores were averaged over all assignments and exams over all students taking the author's classes over all the aforementioned classes that the author has taught in the last six semesters at Pacific.)

In personal conversations with students and on student evaluations of the instructor and the course, some students complained that they sometimes become temporarily uncomfortable at the instructor's questioning, but students also commented that it is probably necessary to continue pushing gently and affably to try to get them (the students) to the point of self-understanding. Several students also commented that they appreciated the efforts that were made to hearten, rally and encourage them while they are being questioned. A few students commented that they felt that the questioning, when done effectively, bolstered their confidence at the same time that it pushed them temporarily and gently off balance.

There is also some anecdotal data that possibly reveals that students eventually understand that the directed questioning is designed to keep them thinking, to motivate them to ask "why," to get them to reason with logical consistency and rhetorical honesty, and to get them to feel the satisfaction of seeing the next step or reaching the answer. The first author of this paper is fortunate to frequently have the same students in successive semesters, and although students sometimes made comments on the evaluations and in person that indicated that they do not always like being questioned, their comments seem to indicate that they are generally more comfortable with this questioning technique in the second or third semester, after they convince themselves that the probing questions probably assist them in eventually finding increased confidence in themselves, leading them to discover what they know and don't know and to develop increased tolerance for working in unfamiliar and uncertain territory. In the course and teacher evaluations and personal conversations, some students also alluded to the importance of feeling that the instructor and the students are mutually supportive and encouraging in the efforts to have a spirited discussion in the classroom.

Additional anecdotal assessment data is revealed during numerous occasions in which co-op students or graduating students and alumni who have come back to the university have described occasions when their supervisors, teammates or customers in industry, graduate or professional school or a government lab have questioned or grilled them in the presence of their co-workers, managers and other engineering professionals, and they commonly proclaim "it was just like in your class!"

Further Analysis of and Reflections on the Socratic Method

This section presents a perspective and views on the Socratic Method as an engineering teaching tool. Recall that the main goals of the Socratic Method for teaching are to help get students actively involved and excited about the material being taught and to help them learn it deeper and retain it better. The purest form of the Socratic Method is when questions (and only questions) are used to arouse curiosity and at the same time serve as a logical, incremental, step-wise guide that enables students to figure out a complex topic or issue with their own thinking and insights. In a less pure form, which is normally the way it occurs in the engineering classroom, students tend to get stuck at some point and need a teacher's explanation of some aspect, or the teacher gets stuck and cannot figure out a question that will get the kind of answer or point desired, or it just becomes more efficient to "tell" what you would like to get across. If "telling" does occur, hopefully by that time, the students have been aroused by the questions to a state of curious receptivity to absorb an explanation that might otherwise have been meaningless to them. Many of the questions are decided before the class; but depending on what answers are given, some questions have to be thought up extemporaneously. Sometimes this is difficult to do, depending on how far from what is anticipated or expected some of the students' answers are.

It helps to have developed a good relationship with the class prior to using Socratic questioning and to establish rapport with the students. Rapport is important for getting them to comfortably and enthusiastically participate in an intellectually uninhibited manner in class and without being psychologically paralyzed by fear of "messing up". Additionally, experience shows that students do not get bored or lose concentration if they are actively participating. In the aforementioned engineering courses, all the students in the class participate; they are all queried by the instructor sequentially one student after another. The instructor can ask the next student whether they agreed or disagreed with a particular answer provided by the student preceding them. It is often possible to obtain significant extra mileage out of a given question that way. If a student does not know the answer to a question, other students often volunteer to bail them out. Calling on a student in a non-threatening way tends to activate others who might otherwise remain silent.

The Socratic questioning method requires a great deal of energy and concentration when you are doing it fast, for example when beginning a new topic. A teacher cannot do the Socratic questioning for every topic nor all day long, at least not the first time a particular topic is taught this way. It takes a great deal of careful preparation and thought. When it goes well, as it often does, it is so exciting for both the students and the teacher that it is difficult to stay at that peak and pace or to change gears or topics. When it does not go as well, it is taxing trying to figure out what you need to modify or what you need to say. It helps to practice the particular sequence of questioning a little bit at least once prior to the real-time lecture, preferably with another teacher. This can help identify flaws in the sequence of questions, and may even provide insights into how to correct them. Preparing for a particular lesson is time consuming. It is also often necessary to re-visit past Socratic-based lessons periodically at a more leisurely pace as the teacher encounters other ideas or circumstances that apply to, or make use of, them. Re-visiting leads to fine-tuning the lesson.

The chief benefits of the Socratic Method are that it excites students' curiosity and arouses their thinking, rather than stifling it. It also makes teaching more interesting, because often, the teacher learns new insights and knowledge from the students, or by the questions and insights that they make you reflect upon and think of. Each group of students is just sufficiently different, that it makes the classroom experience stimulating for almost everyone involved. It is an efficient teaching method, because the first time through tends to cover the topic very thoroughly, in terms of the students' understanding of it. It is more efficient for their learning than pure classical lecturing to them is, though, of course, a teacher can lecture in less time than it takes to develop the same concept or problem solution via Socratic questioning.

Using the Socratic Method yields constant, immediate feedback and thus allows real-time monitoring of the students' understanding as the class progresses, and this way the instructor receives rapid, valuable feedback on the problems and misunderstandings or lack of understandings the teacher needs to address as he/she is presenting the material. The teacher does not need to wait to give a quiz or exam; Socratic questioning is one big real-time quiz, though a quiz whose point is teaching, not grading. Though, to repeat, this is teaching by stimulating students' thinking in certain focused areas, in order to draw ideas out of them; it is not "teaching" by pushing ideas into students that they may or may not be able to absorb or assimilate. Further, by quizzing and monitoring their understanding as the class moves along and progresses, the instructor has the time and opportunity to correct misunderstandings or help students who are in the process of getting lost immediately in real-time, not at the end of five-six weeks when it is usually too late to try to "go back" over the large amount of material that has already been covered.

Socratic questioning encourages students to think creatively and to come up with ideas that are new (or at least new to them), and in some cases students' ideas jump ahead to new material so that you can meaningfully talk about some of it "out of (your) order" (but in an order relevant to them). Or you can tell them you will get to exactly that material in a little while, and will answer their question then. Or you may suggest they might want to think about it between now and then to see whether they can figure it out for themselves first. There are various options, but what is common to all these options is that the material is "live" for the students, which it is not always the case when the instructor is plain lecturing or just telling the students things and students are passively and dutifully taking notes or listening without much thinking.

If the instructor asks the right questions in the right sequence (this take practice), students in the full intellectual spectrum in a normal class can progress at about the same pace without being bored; and they can "feed off" each others' answers. Gifted students may have additional insights they are often eager to share at the time, but even if they may not share at the time, they will tend to reflect on later. This brings up the issue of teacher expectations. Some students who are not in the "top" group of students sometimes have lower expectations of themselves and they sometimes feel they get teachers who expect little of them, and who teach them in boring ways because of it. But applying the Socratic questioning equitably and kindly in the classroom stimulates and challenges all students as much as possible. The Socratic Method is an excellent way to include all students in a lively, effective discussion. It works for most topics or parts of topics that have a logical nature. The Socratic Method does not work for unrelated facts or for explaining conventions, such as items that are more the result of historical accident than logical selection.

Socratic questions are specific, and as logically leading as possible. That is part of the point of the Method. Some questions are not as good as others, particularly not broad, open-ended questions, like "What is mathematics?" or "How would you design an (binary) arithmetic with only two numbers?" Students have nothing in particular to focus on and latch on when you ask such questions, and few come up with any sort of interesting answer.

Socratic questioning forces the teacher to think about the logic of a topic, and how to make it most easily assimilated. In tandem with that, the teacher has to try to understand at what level the students are, and what prior knowledge they may have that will help them assimilate what the teacher wants them to learn. Socratic reasoning/questioning emphasizes student understanding, rather than teacher presentation; student intake, interpretation, and "construction", rather than teacher output. And the point of Socratic education is that the students are helped most efficiently to learn by a teacher, not that the teacher make the finest apparent presentation, regardless of what students might be learning, or not learning.

The four critical issues about Socratic questions are as follows: 1) they must be interesting or intriguing to the students; they must lead by 2) incremental and 3) logical steps (from the students' prior knowledge or understanding) in order to be readily answered and, at some point, seen to be evidence toward a conclusion, not just individual, isolated points; and 4) they must be designed to get the student to see particular points. You are essentially trying to get students to use their own logic and therefore expose, by their own reflections on your questions, either the good new ideas or the obviously erroneous ideas that are the consequences of their established ideas, knowledge, or beliefs. Therefore you have to know or to be able to find out what the students' prior well-established ideas and beliefs are. This is generally better than just asking any question or starting just anywhere.

It is crucial to understand the difference between "logically" leading questions and "psychologically" leading questions. Logically leading questions require understanding of the concepts and principles involved in order to be answered correctly; psychologically leading questions can be answered by students' keying in on clues other than the logic of the content. For the Socratic Method to work as a teaching tool and not just as a magic trick to get students to give the right answers with no real understanding, it is crucial that the important questions in the sequence must be logically leading rather than psychologically leading. There is no magic formula for doing this, but one of the tests for determining whether you have likely done it is to try to see whether leaving out some key steps still allows people to give correct answers to questions and problems they are not likely to really understand. Further, experience with using Socratic inquiry shows that when you use a good, well-taught-out, carefully designed sequence of questions with impatient or math-phobic students who didn't want to have to think but just wanted you to "get to the point", they usually cannot correctly answer very far into even a relatively simple sequence of questions.

Answering most of these questions correctly requires, generally, understanding of the topic rather than picking up some "external" sorts of clues in order to just guess correctly. Moreover, generally when the Socratic Method is used, it tends to become pretty clear when students get lost and are either mistaken or just guessing. Their demeanor tends to change when they are guessing, and they answer with a questioning tone in their voice. Further, when they understand the material and the logic and rationale behind it as they progress through the give-and-take of the Socratic discussion, they tend to express out loud insights they have acquired or reasons they have for their answers. When they are just guessing, they tend to just give short answers with almost no comment or enthusiasm. They don’t tend to want to sustain the activity.

Two of the interesting benefits of using the Socratic Method are that (i) it gives the students a chance to experience the attendant joy and excitement of discovering (often complex) ideas on their own, and (ii) it gives teachers a chance to learn how much more inventive and bright a great many more students are than usually appear to be when they are primarily passive. Human progress depends on asking questions and on persistently pushing and challenging ourselves to seek to discover the answers. In a sense, through the directed Socratic questioning, the instructor tries to keep the students and the teacher temporarily off balance, forcing the participants to step into challenges that we are not at all sure we can handle, leading us into places where we feel somewhat uncomfortable, where the students and the instructor may feel we don't know enough, where we cannot slide by on past knowledge. As soon as the students and the instructor have mastered something, the teacher affably and gently pushes everyone past the edge of our comfort zone, striving to make us temporarily uncomfortable, to challenge our confidence so we can learn new things and earn a new confidence. This often results in beautiful moments when students gain new perspective and insight.

The Socratic Method is an effective tool to encourage an intellectual dissonance to compel students to examine their knowledge and to challenge their own assumptions about it, to question what they assume to be "natural" or taken-for-granted, to prompt students to determine the best approach to problem solution by themselves, to critically and rationally examine the engineering and scientific concepts and problems, and to travel as far as possible, under their own power, to arrive at their own deep understanding and insight.

The Socratic Method is a good way to teach engineering and science because the students are constantly challenged to give answers not found in their textbooks, and then to respond to a close scrutiny of these answers. In using the method, the teacher gently and affably puts to students the next question they should be asking themselves. The instructor listens carefully to students, trying always to understand what they have to say, and to find what is good or interesting in what they have said. In the classroom the instructor tries hard to develop a friendly atmosphere in which students are not afraid to work at the edge of their knowledge, saying things that they are not sure are right, but which, because they are on the edge of certainty, are lively, interesting thoughts.

The Socratic teacher does not intend by his or her style of teaching to allow students' ideas to escape rigorous scrutiny. Quite the contrary: they try to establish an atmosphere in which the instructor can cordially and good-naturedly say the most direct and critical things about a student’s answer or idea, without the student feeling that he or she has been personally attacked. It is important to correct and contradict the students without intimidating or humiliating them. Besides, the teacher’s own ideas are usually on the table together with those of students, and they undergo similar dissection and are subject to the same tests of consistency and verifiability. When students know that they will be treated respectfully as well as rigorously and honestly, they are encouraged to volunteer risky ideas and they usually see the instructor’s comments not as a threat, but as a road sign, pointing them in the right direction. When the classroom is at its best (which is not always), the conversation turns back on the instructor: students contradict the teacher, argue with him/her, and vigorously defend their own ideas. It takes courage for students to do this, and it is gratifying to see in students that spark of discovery and excitement.

Summary

We all value the skills of reasoning and critical intelligence; Socratic questioning teaches these – and much more. Indeed, the Socratic Method is a good vehicle for stimulating undergraduate engineering research, fostering tolerance and open mindedness, instigating engagement with the course and lab material in almost any engineering course, promoting understanding of global connections and inculcating the method of multidisciplinarity. The Socratic Method constitutes a series of connected academic experiences and teaches students to ask questions and seek answers to serious academic and real-world questions. Participation in Socratic debate, at any level, can have positive consequence for students and faculty alike: both students and faculty participating in the engineering courses reported in this paper have noticeably sharpened their logical, critical and rational thinking; learned to articulate ideas; learned to understand the processes and value of making judgment calls and tradeoffs; confronted the complexity of the subject matter in many of its forms; and learned to develop a more balanced approach to complex problems.

Compared to intercollegiate athletics and other costly endeavors, Socratic questioning/debating is, dollar for dollar, an efficient use of institutional resources. It requires no multimillion dollar complexes, playing fields, stadiums or expensive equipment. All that is necessary are classrooms, coaches, office supplies and support for travel and research. Socratic questioning/reasoning is a relatively inexpensive, educational and effective way to enhance the quality of the academic experience.

Engineering faculty using Socratic reasoning in the classroom are not necessarily bold innovators in teaching techniques or the development of experimental teaching materials. Socratic questioning de-emphasizes "teaching" and concentrates on persuading students to learn at least the essence of the material we are trying to get across. Socratic persuasion strives to keep the student learning process vital through a variety of means: by frequent questioning, answering and give-and-take; by closely and frequently interacting with students as the individuals they are, with sensitivity to the unique needs, objectives, problems and constraints of individual students; by being open to students in all their peculiarities and particularities, and accepting them for who they are; by communicating with students at a level and intensity that seem optimal for each individual student's development; designing courses, as well as the faculty's participation in them, to maximize one-on-one or small-group interactions; lectures, labs and projects that are sensible and interesting (not confusing or boring); a range of teaching assignments that runs from first-year classes to specialized advanced electives, projects and seminars; repeated revision of lectures, laboratory assignments and projects; the regular creation of new topics for electives and seminars; and an insistence upon exposing my own ideas to scrutiny and reaction.

Every time most engineering educators enter a classroom or lab, they probably have two main objectives. First, they want students to learn. When we teachers are too pleasantly relaxed and too confident of ourselves we may become somewhat self-satisfied and smug and we probably do not learn as well as we could. We probably learn the most when our self-confidence and self-contentment are endangered. It is beneficial, then, as part of our strategy to sometimes keep our composure temporarily out of equilibrium and to frequently challenge what we hold as conventional wisdom. The value of our learning and teaching often rests on our willingness to be temporarily a disturber of the peace, to afflict the comfortable, the complacent, and the indifferent in ourselves and in our students.

Socratic teaching is a process by which the teacher seeks to gently stir and challenge the students' (and the teacher's) intellect, to kindly shake it up, to prevent it from becoming complacent. Socratic teaching seeks to deepen the students' – and the instructor's – reasoning skills and to develop our insight and imagination, often by asking questions we are not fully comfortable answering. This "rocking the boat" often results in a lively exchange with students; this exchange is the spark that keeps intellectual curiosity burning strong. Seeing the faces of students brighten when they answer a difficult question or conquer a difficult concept is a powerful, enjoyable feeling. The Socratic Method is most effective when the teacher has established rapport with the students; it is important to convince students that the faculty person is available to them. The Method works better when we try to be responsive to any question a student comes up with, when we never lower our students' confidence by the way we answer a question. It is important to seek to build students' confidence with the knowledge that they now have the answer to that question and the sum total of what they know is growing constantly. This way, students walk out of class or lab feeling that they not only collected facts and ideas but also sensed the excitement of discovery.

Socratic teaching works to help students understand, through our everyday interactions and engagements, what it means to live in a world of mutual respect, shared values, and collective goals. The keywords of Socratic teaching include *passion*, *caring for the students*, *relevance, practicality, love of subject, enthusiasm, knowledge, preparation, organization, feedback*, *approachability, accessibility, playfulness,* and *curiosity*. But like the keywords to journal articles, these terms alone cannot convey the Socratic approach to teaching. These keywords are more like adjectives and adverbs that modify a set of principles which are difficult to articulate. Maybe the essence of the Socratic approach is to create the desire to learn, lay ample opportunities for learning in the students' path, make sure these opportunities contain things worth knowing, convey the information with clarity and enthusiasm, and provide the most invigorating and supportive environment possible in which the learning can flourish, an environment that will stimulate students to continue exploring, discovering and developing their powers and motivate them to continue to grow in their knowledge of the subject and of themselves.

Bibliography

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