# A COLLECTION OF OBSERVATIONS AND ADVICE ON UNIVERSITY TEACHING

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## Outline



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## A Prime Directive: Don't Bore the Students

A great deal of my teaching philosophy flows from this one maxim: Don't bore the students. If the lecture lacks luster, attendance and enthusiasm drop, and a moribund, self-feeding feeling sets in. Teaching and learning become drudgery. Conversely, classroom sparkle grows in a positive feedback loop: more students, more witty questions, more sparkle.

Most of us have a vague goal of "making lectures interesting," yet we're notoriously bad at it, as any undergraduate will testify. "Please don't become jaded like some other professors," an undergraduate student pleaded with me in course comments at the end of my first semester. What did this student mean? My interpretation of this memorable comment will always be that despite the intense pressures of building up a research program, securing funding, and publishing, I must never become indifferent to teaching. A professor is a teacher first of all.

Students understand that we've got obligations besides teaching. When they plead for more verve in the classroom, they're not necessarily asking us to devote more time, but rather to more effectively use the time we already devote. Subsequent sections on listening, memorable illustrations, puzzlement, research-infused teaching, and logistics will treat the "do's,": key ingredients of classroom dynamism. Here I'll discuss the "dont's," or paths to boredom.

**Lack of Context.** Suppose your topic is the structure of a GPS signal. You lay out a model for the signal in the form of an equation for the received samples, pedantically labeling each of the components. The equation includes all the important parts and their mutual relationships. It's all the students really *need* to know to work with the signal. But the students won't find the signal structure *memorable* or *interesting* because it's been offered without context.

The same 15-minute presentation of the signal structure can be made much livelier with a short stage-setting prelude: "As it turns out, the early designers of the GPS signals agonized over the choice of broadcast frequency: too low and the signals would be absorbed in a disturbed ionosphere; too high and they wouldn't penetrate even tree leaves. There was also debate about how to provide multiple access. Fortunately the US settled on code-division; the Soviets, who were slavishly copying the GPS system in all other respects, made the fateful decision to adopt frequency division. They're still regretting that today, as I'll explain later." One then launches into the signal structure model, tying components as appropriate to the drama of their development. Adding context extends the discussion by perhaps an extra five minutes, but these are minutes well spent. The students now understand that the current signal structure isn't the only way things could have turned out; they're more aware of the engineering decisions that had to be made; and they feel empowered to question other aspects of the signal structure.

**Obviousness.** In one way of viewing it, the information content of a classroom discussion is inversely proportional to the obviousness of statements made. An exposition can be clear without being uniformly obvious. Boredom-inducing obviousness is most likely found in the way we professors phrase our questions. It's fine to toss out a few matter-of-fact questions (e.g., "How many constants of the motion are required for solution of the 3-body problem?") just to see whether students are following along, but the real novelty—and learning—comes by asking clear but puzzling questions. The connection between puzzlement and enlightenment will be further discussed in a later section.

**Enthusiasm without Substance.** One might expect that enlivening the classroom experience is simply a matter of smiling more, moving about, modulating one's voice, and clapping one's hands together for dramatic effect. To bring enthusiasm into the classroom, just be enthusiastic!

But students are looking for purposeful enthusiasm—enthusiasm that values, not wastes, their time. There is nothing more tiresome than unending action sequences hung on a thin plot—witness Pirates of the Caribbean III. So the anecdotes we add to lecture must be an enhancement of, and not a substitute for, a rigorous technical discussion. I recall a painful semester of Mechatronics at Cornell in which the professor would punctuate his dry chalkboard work with unrelated anecdotes from his days at DARPA. They kept students from falling asleep, but the spicy stories weren't focused on the substance of the lecture, and the equations and concepts were soon forgotten.

## The Secret to Classroom Buzz: Listen to, and Play Off, Students' Questions

It's not practical to think of the classroom experience as one long exciting conversation with the professor acting merely as a discussion facilitator. Students internalize concepts well in this kind of discovery learning environment, but they internalize altogether too few concepts. There is a great deal of material to be mastered in engineering! And given that future courses build directly off present ones, a professor who eliminates a third of the standard content from an engineering course—as I was advised to do by a professor from a non-engineering discipline when I arrived at UT—shortchanges his or her students in the long run.

On the other hand, students learn best when they participate. The art of teaching involves knowing how to strike the right balance between covering more material and eliciting more student participation in the learning process: It's a classical tradeoff of educational breadth versus potency.

My approach to this tradeoff is to intersperse a fairly traditional lecture with two or three intense question-and-answer segments. Sometimes I'll begin the questioning; sometimes it's the students who start off. If successful, these brief back-and-forth interludes set the classroom abuzz. Success depends on getting students to ask meaningful questions, and this, I've found, depends on my paying close attention to their earlier questions and proving to them that I've done so.

Most students want to participate. They find it enjoyable and they know it helps them learn. But they'll see no point in participating if the professor brushes off their questions with a cursory response or is clearly preoccupied with other thoughts as they're speaking. To keep my focus on students' questions despite other thoughts I might have spinning in my head, and to demonstrate to students that I'm listening, I try follow these "R's" when a students asks a non-trivial question:

- Recognize the student by name (easy for small classes; harder for large classes).
- Restate the question in my own words.
- Reformulate, redirect, or respond: Reformulate the question in a way that the student recognizes the answer (best outcome); or redirect the question to the rest of the class (next best, time permitting); or respond directly (least effective technique, but often appropriate).
- Riff off of the question to emphasize a point or make a transition into the next stage of the lecture.
- Refer back to the question if something later in the same lecture offers further clarification.
- Refer back to the question in *later lectures* if it was particularly insightful.

I can't overemphasize the potency of these "R's" in engaging students and thereby deepening each student's understanding of the concepts presented. If the secret to learning is participation, the secret to participation is making students feel smart and insightful when they open their mouths.

## Puzzle, Enlighten, Repeat

To supplement my income during my undergraduate years I turned a childhood fascination with magic into a part-time job, performing magic shows at children's birthday parties and school functions. Much of my teaching style is adapted from my years as an itinerant magician.

The attraction of stage magic depends on one's maturity. Younger children are captivated by the wonder and humor of surprising outcomes; older children can't rest until they've figured out how it's done. On my first brush with magic at fourteen I was old enough to be part of this latter group. A magician took three ropes that I had just tied in loops, each with a tight square knot, and effortlessly linked them together. Years and many magic books later I found the trick and finally satisfied my burning curiosity. The Magical Linked Ropes is now part of my standard routine.

Puzzlement is a powerful—and fairly universal—impetus to learning. Confronted with our own ignorance in the face of a simply-stated paradox, we probe a thousand directions in our mind, reasoning out constraints along the way that winnow the possibilities. This is the deepest kind of problem solving; a puzzle is at once a test and an exercise of learning. The payoff is a satisfying sense of wonder and relief when the breakthrough comes. The tension of puzzlement and the release of enlightenment makes puzzle-solving or paradox-resolving genuinely enjoyable.

My lectures are often structured around paradoxes. After introducing the context, I commonly lead into a new topic with a puzzling question or series of questions, which I write down completely on the board. Some of these are meant to be resolved during lecture, others are take-home puzzlers given for extra credit. For puzzling questions that are to be resolved during lecture, I either (1) solicit a response from volunteers across the whole class, (2) call on a student by name, or (3) ask the students to pair up and discuss the puzzle for about a minute, after which I call on one group to give us their insights.

Like a good magic trick, the simpler the puzzle and the cleaner the presentation, the more captivating. Puzzling questions don't necessarily have to be paradoxical or tricky. The hallmark of a puzzling question is that it pushes us to think beyond the immediate constraints that we've been presented with, extrapolating to other logical constraints, and thereby identify a family of plausible answers. Here are some examples drawn from my lecture notes:

**Q:** Why are there only 8 planets in our solar system; no more, no less? (This question, from my undergraduate Spacecraft Dynamics course, is meant to connect students with Johannes Kepler's way of thinking. He saw deep metaphysical meaning in the number of known planets—5 in his day.)

**Q:** If we have Newton's three laws of motion and his gravitational law, do we also need Kepler's laws to solve the two-body problem? (Also from my undergraduate Spacecraft Dynamics course, this question often initially gets answered "yes." But students realize upon further reflection that Kepler's laws are *embedded* in Newton's laws—Kepler's laws were the constraints by which Newton derived his laws. This leads to a discussion of mathematical parsimony.)

**Q:** From the perspective of an observer on Earth, the clocks in GPS satellite tend to run slow due to special relativity and fast due to general relativity. Could these two effects possibly cancel out at a certain altitude? (I presented this question during lecture in my undergraduate Satellite Navigation course and offered 5 points extra credit for the first student to email me a correct response. Almost all students responded.)

**Q:** Should calculation of the time of flight account for ionospheric and tropospheric delays? If so, then why isn't it redundant to also include the delays $I$ and $T$ in the measurement equations? (This question, from an exam in my undergraduate Satellite Navigation course, challenges the students to recognize that the signal delay introduced by the ionosphere and troposphere has to be accounted for in two seemingly unrelated ways.)

**Q:** If the carrier wavelength is 19 cm and the code chip interval is equivalent to 300 meters, how is it possible for a GPS receiver to measure phase to millimeters and pseudorange to meters? (From my graduate-level GPS Signal Processing course, this question is meant to emphasize the precision made possible by low-bandwidth feedback tracking.)

## Memorable Illustrations

Richard Feynman was famous for his memorable illustrations. When explaining Snell's law, he asked his students to consider how they would go about rescuing a struggling ocean swimmer. (Feynman added a questionable bit about the swimmer being a beautiful girl, no doubt making the illustration more memorable for his all-male audience.) Starting from a random point on the beach, would they make a direct line for the swimmer or would they take an indirect dog-leg path given that they could run faster than swim? With a moment's reflection the students saw the efficiency of the dog-leg trajectory. Besides giving them some practical first-aid advice, Feynman cemented with this illustration the principle of Snell's law forever in their memories.

My favorite teachers have all had Feynman's gift for memorable illustrations or analogies, from Jesus to Hume to Feynman and others more contemporary. To evoke an illustration is to tell a short story, and our brains are wired to remember stories. My students will attest that I make liberal use of far-fetched analogies in an effort to give them an indelible conceptual hook. For added effect, I often refer back to these analogies in exams.

## Old School, Chalk and Notes

I recently heard a professor who was advocating in-class peer instruction deride the traditional chalk-and-notes lecture format. "If you'd like to come by my office hours and have me copy my lecture notes onto the board so that you can copy them from the board into your notes," he told a student, "then by all means drop by. But in lecture we'll make more effective use of our time." The professor's dismissal sounds convincing at first. Why should we professors so pedantically write notes on the board just so our students can pedantically copy those notes into their notebooks? Besides being inefficient, the chalk-and-notes approach sounds dull. Shouldn't we instead distribute notes beforehand and devote class time to a discussion spiced with PowerPoint slides, relieving both the instructor and the students of the need to write anything in class?

I don't think so, for the following reasons:

(1) I reject the notion that a chalk-and-notes format is necessarily dull. The professor's glib comment above is misleading. While copying is indeed a large part of a traditional lecture, a skillful teacher creates an environment in which riveting interludes of interpretation, questioning, and discussion naturally arise between segments of note-taking.

(2) It is profoundly empowering for students to realize at semester's end that their notebooks have become a course textbook written in their own hand. In the margins are found interpretive comments made during moments of clarity. To achieve this conversion from mere notes to course textbook, the lecture notes as presented must be well-organized and complete. Furthermore, the students must take care to fix errors and make updates, re-doing entire lectures if necessary. An instructor who is fussy about what goes into students' notes, returning to previous lectures to remedy errors that were introduced during lecture, reinforces the notes-as-textbook ethos.

(3) The scope of what was covered in the course is often in question around exam time. I make a guarantee to my students that all the material on exams can be addressed by a combination of course notes, homework, and logical extrapolation. Having a record of exactly what was presented during lecture has been crucial in justifying and explaining exam questions after-the-fact.

(4) PowerPoint slides can be an effective supplement to a lecture but should be used sparingly; they are otherwise soporific. A visualization or animation does wonders to extend

or reinforce a concept introduced on the board, but presenting lecture notes on the screen instead of on the black (or white) board is the surest way to sap a lecture of its vigor.

(5) Students learn best when they take notes during class and review those notes often. The act of writing down what is written on the board isn't a mindless one. The words, notation, and concepts pass at least once through the students' ears, minds, and fingers out onto the paper. Once the students have written something down, no matter how unclear their initial thoughts on the subject, it's no longer foreign. There is simply no substitute for personal notes. I tell students that I know it's painful to write so much, but I promise them that they'll learn more. In a gesture of solidarity, I point out that they'll be proud of their calloused fingers by the end of the course and I'll be proud of my sore arm.

## Research and Teaching Fusion

One way to promote excellent teaching at a top research university is to adopt the perspective that teaching is a research tool and that research is a teaching tool.

**Teaching as a Research Tool.** On this view, professors see their time in the classroom as the most effective way to sharpen their own thinking, to prepare their current students for research, and to recruit new students. The teaching-as-a-research-tool viewpoint works for both undergraduate and graduate courses. Bright undergraduate students who found value in my spacecraft dynamics courses have joined my lab as undergraduate research assistants. Besides adding value to the laboratory, these students position themselves well for research-intensive graduate study. One of my erstwhile undergraduate assistants is now one of my star graduate students.

Moreover, classroom instruction acts as a constant reminder to both lecturer and students of the current limitations in the field. This is true because a good instructor points out where the theory is on shaky footing, and because if a topic cannot be explained in an undergraduate lecture, it is not yet fully understood. Thus, classroom exposition becomes a metric for evaluating research maturity.

**Research as a Teaching Tool.** Classroom material has a shorter shelf life than many of us would wish. Each year our lecture notes and assignments need review. Are the models still current? Do the tools represent the latest thinking on the subject? Beyond the technical material, the narrative that motivates and gives context to our field of study must be kept fresh. Students notice the cobwebs in our lectures and discussions.

In most cases, the graduate-level courses we teach are closely tied with our research interests, so vitalizing our courses with an infusion of current research, whether ours or the students', is effortless and enjoyable.

With undergraduate courses, we must be more creative. Material covered in undergraduate courses is typically mature, which only heightens the need for a vitalizing conduit from our research laboratories into the classroom. But in some cases the subjects we teach are far from our core research objectives. So undergraduate courses suffer from a double disadvantage: maturity and inactivity.

The undergraduate spacecraft dynamics course, which I've now taught twice, is a good example of this problem. The models and techniques used in undergraduate spacecraft dynamics are more than 20 years old and still perfectly adequate. Moreover, my field of research, radionavigation, is only peripherally related to spacecraft dynamics. So how to keep the classroom discussion from going stale?

My technique has been to exploit the overlap with my own research insofar as I can, and then pull in research being conducted elsewhere at the university. Drawing material from my colleagues has the triple benefit of keeping the lecture material current, helping me and my students become familiar with my colleagues' research, and raising my colleagues' esteem in the eyes of the students. When discussing the non-uniform gravitational field of celestial bodies, for example, I highlight the work that Byron Tapley's team at the Center for Space Research has done to map out the Earth's gravitational potential to an unprecedented resolution. When developing the rocket equation and contemplating the expense of launching mass into space, I can tell students about the rail gun that Hans Mark envisions. For an example of how to approach trajectory optimization in multi-body problems, I can point to the Copernicus software, which my colleague Cesar Ocampo developed. And as long as my colleague Glenn Lightsey and his Satellite Design Lab keep launching nanosatellites, I can discuss low-earth-orbit trajectories in concrete terms of University of Texas-launched spacecraft.

## Backstage

A good course involves extensive "backstage" work outside the lecture hall. This includes developing quality syllabuses, assignments, and exams; offering individual or small-group interaction during office hours; maintaining the course website; and, yes, grading. I tell students who only audit my courses that they're missing out on half the learning.

My teaching assistants and I make extensive use of Blackboard as the course website. By offloading to Blackboard the posting of lecture supplements, announcements, and grades, we free up class time for substantive instruction and discussion. Some effort on the back-end makes the front-end (lectures) more potent and enjoyable.

I view written communication with students as contractual. The course syllabus acts as a contract between the students and the professor. Accordingly, I offer exceptions to the stated norms of the syllabus only in extraordinary circumstances. In announcement postings on Blackboard, I remind students of important dates and tell them what to expect on upcoming assignments and exams. I then endeavor to follow through to the letter on these postings. Course assignments and exams are also contractual. Every word, every problem must be unambiguous so that students know exactly what is expected. The point value of each problem should be noted so that students know how to allocate their time. Once expectations are properly communicated, it is easier to make grading consistent and transparent. Grading becomes an exercise in determining whether the student's response is contractually compliant.

Out-of-class communication is much easier to tailor to individual needs than in-class instruction. By email, I sometimes reach out to students who are working hard but performing poorly, inviting them to meet with me during my office hours. Likewise, I send personal emails to the top performers in the class congratulating them on their test grades, etc. Insofar as my time (and the class size) permits, I want students to know that I consider them individually and want each one to succeed.

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