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Due to technical difficulties, only a portion of lecture one is available for viewing.

PROFESSOR: Welcome to Teaching College-Level Science and engineering. The title contains the word teaching, which may spark some questions in your mind. For example, is teaching just an art? Or is it something that's just something you're born with? In which case, either you have it or you don't have it.

Well, obviously, I don't believe that, or I wouldn't be teaching a course on it. What would be the point? Or is it purely a science where there's a set of equations and procedures to learn, and then all of a sudden, you'll be an excellent teacher?

Well, actually, it's neither. And it's both. It's things that we're all born with, on the one hand. And there're also procedures and techniques and ways of thinking that will improve how you teach and that we can all learn. So it's a happy mix, my favorite mix, an art and a science.

So another example that's an art and the science is book design. So compared to, for example, just pure art-- painting, say modern painting-- very unconstrained, versus say biology procedures in the laboratory, very, very closely specified. It's somewhere in between. There's an art-- all the arts of color, space-- but they all have to be used together to achieve a particular purpose.

So again, in there, there's some beautifully designed books and some not so beautifully designed books. And there're principles behind that that we can use to design good books. And similarly, there are principles we can use to design good teaching. So the whole point of this semester is to design good teaching and how you do that.

And rather than me give you a big long theory about it, because actually there isn't really theory so much in the equivalent to, say, Einstein's theory of relativity. But there's principles to learn. The best way to learn those principles is with an example.

So what we're going to do today is I'm going to do an example of teaching with you. We're going to do a sort of maybe slightly sped-up version of what we would normally do, say, if we were actually using this example in a class. Then we're going to analyze why it was done that way.

And from that analysis, general principles of teaching will come out that will be addressed throughout the semester. And they'll be addressed in the context of particular tasks. Like for example, how to make slides that are useful for teaching, how to use a blackboard, how to teach equations, how to design a whole course, how to make problems.

So all of those tasks will be the week by week subjects. And in each task, all of the principles that we're going to talk about now will show up in those tasks. And you'll see the principles illustrated repeatedly.

OK, so the problem-- one of my favorites. So these are two cones. One has twice the dimensions of the other cone. So let me show you how I made the cones.

So I printed out a circle and just cut out one quarter of the circle. And then I taped this edge to that edge. Or in mathematician speak, I identified the edges, which now I know means I taped the edges together. And then you get a cone, like that.

So this cone and the other cone were cut out of the same sheet of paper except this one has twice the linear dimensions in its circle. So I think this circle was 7 centimeters in radius, and this is 3 and 1/2 centimeters in radius. So other than that, they're the same. And the question is, which one has the higher terminal velocity? Or are they about comparable?

So in particular, the question is this. So I'm going to drop them. And the question is, what's their ratio of their terminal velocities?

So the ratio of the big cone's terminal velocity to the small cone's terminal velocity is equal to what. And you get choices along this axis. So here is--

OK, so those are the five regions to choose from. So you have five choices for the ratio, basically roughly $1/4$. This is some range here, because nothing's exact. And we're certainly not going to do an exact experiment. Roughly $1/2$, roughly 1, roughly 2, or roughly 4.

So does everyone understand the question? Because you're going to get to try it yourself. Question about the question?

AUDIENCE: If you could restate it-- actually, there was a sign-up sheet going around which distracted me. So I sort of lost the--

PROFESSOR: Sure. Could I restate the question? No problem. So I'm going to drop them, just like this. No tricks-- I'm not going to flip this one around or anything.

And the question is, what's the ratio of their terminal speed? So right away, as soon as you let go of them, they come to a steady speed, which is their terminal velocity. And the question is, how do the terminal speeds of the big one and the small one differ?

OK, so in particular, the question is, what's the ratio? And there's five choices for them. Does that help?

AUDIENCE: Yeah. So what were the dimension of them again?

PROFESSOR: So this guy is-- he was cut out of a circle who was 7 centimeters in radius. And this guy was cut out of a circle who was 3 and $1/2$ centimeters in radius. And then I was also very careful to use-- let's see. Did I do this right? Yeah, I used to half the width of tape on the small guy as I did on the big guy, just to get it really very perfectly scale invariant. OK any questions about the question?

OK, so think to yourself for about 30 seconds or so, just to induct yourself into the problem. And then we'll take a vote. And then you'll have a chance to discuss it with each other.

OK, let's just take a vote. So I recognize I haven't given you at all enough time to come up with an exact answer or calculate everything. And that's by design. So let's just get a straw poll. And then you'll have a chance to argue with your neighbor about it.

So who votes for 1/4, which is that the-- so let's see-- 1, 2, 3, 4, 5, 6. OK, 6. Who votes for 1/2? 1, 2, 3, 4, 5, 6, 7-- 12. Who votes for C? 22. Who votes for D? No takers. No takers for D. OK, how about E?

OK. So now find a neighbor or two, one or two neighbors. Introduce yourself to your neighbor. And also, by the way, unless you're taking notes on your laptop and really insist on doing that, if you could close your laptop, that would be very helpful for the purpose of discussion in this whole course.

So find a neighbor or two. Introduce yourself. You'll be getting a chance to meet graduate students from across the institute. This is a great opportunity.

And try to convince them of your answer, especially if you have a different answer. Or if you happen to share an answer, well, see if you can figure out why you're sure of it. Or if you're not sure of it, see if you can settle that.

OK, so discussion time. And if you have any questions that come up as you're discussing, raise your hand. And I'll come and wander over.

Meanwhile I also handed out feedback sheets for the end of the session, which I'll ask you to just spend a minute on at the end. But you'll notice one of the questions is, what's the most confusing thing? So if anything really confusing comes up during the whole session, you can just put it right then. You don't have to wait till the end. Or if there's something you really liked or hated-- that's question two-- you can put that whenever it happens to come up.

But vote number two, and then we'll take some reasons. So 1/4? 1, 2, 3. OK, 4. 1/2-- the halves don't have it. Oh, no, there's 1. Oh, there's 2. OK great-- 3, 4, 5, 6. Equal? OK, so that's about-- let's call it 30. 2? And 4.

OK so thanks for the votes. Let's take reasons for any of them. I'll take reasons for any of them, and I'll put them up here. You don't even have to agree with the reason. It's just something you guys discussed and thought maybe was plausible.

AUDIENCE: C seems to have [INAUDIBLE]. When you do this kind of activities, there is always some guys who have seen it before. And he may choose to spoil it. So I may want to know what you would do in that kind of situation.

PROFESSOR: So you're-- hm. I'm not sure how to phrase this. Let me just take other comments. I'll come to it afterwards. Other comments for any of the reasons?

So again, it doesn't have to be things you necessarily believe, but things that are plausible. And that's actually more instructive than what you think is for sure right. Because now you're trying to figure out what might be true. And you're expanding the ways you're thinking. Yeah?

AUDIENCE: C, because they have identical mass to surface area ratio.

PROFESSOR: OK. C, so mass to area ratio is the same. OK, can people think of plausible reasons against that argument? Yes.

AUDIENCE: So I have no idea what the actual formula is for calculating it. If there was a square in there, then that would [INAUDIBLE].

PROFESSOR: Right. So I'll call this Not C. So suppose the formula actually depended on the square root of A or square of A or something like that. It's, say, one chance out of three that it has A to the first power here. It could have A to the 1/2 or A to the 2. So could be m over A to the k for k not equal to 1. Others for or against C, intuitive reasons, or for any of the others? So hopefully that's-- oh, yes. Go ahead.

AUDIENCE: [INAUDIBLE] The air resistance scales with the area. And the gravitational force would normally scale with the volume, [? except that it's ?] in the surface, [INAUDIBLE].

PROFESSOR: OK, so let's see. F drag proportional to area and weight proportional to area. So

that's an argument for which choice?

AUDIENCE: For C.

PROFESSOR: For C, OK. How do you know that the drag scales with the area? Maybe it scales with square root of area. Any arguments pro or con? OK, yeah.

AUDIENCE: You could argue that it scales with the area because then you just break it up into decimal pieces. Each one has the same force intensity.

PROFESSOR: OK, so for this, let's say there's a thought experiment of subdividing. So I'll just note that as Subdividing Thought Experiment. OK, yeah.

AUDIENCE: But then if you have some weird shape, the air has to flow through hitting some pieces and then flow through the rest of the pieces. So that [INAUDIBLE] may not work. [INAUDIBLE]

PROFESSOR: So it may depend on the geometry. So I'll put that up here as Geometry. What else might depend on? For example, is air resistance, say, always proportional to area? Hm. Yep?

AUDIENCE: It could depend on the material, surface roughness or something.

PROFESSOR: OK, so it might depend on the material. And it certainly does, which is actually one reason I was very careful to construct them out of the same piece of paper. So let me put this is the material. So the surface roughness. Yeah?

AUDIENCE: Well, this may not be relevant given how you said you dropped them. But it also might depend on [? exactly how they ?] fall.

PROFESSOR: Right, OK, so whether they fall vertically or downward. Yeah, that's true. So it might depend on the way I drop them. So actually, yeah, to make us not have to worry about that, I'll just drop them simultaneously pointing downwards.

Yeah, so the fall configuration. So there's all these other variables. So let's do the experiment. Then I'll come back to your question.

So let's do the experiment this way, which is that I will stand on the table and pray that I have matching socks on, which is sort of 80% these days. It's increased. And I will drop them on the count of three.

Are they both about-- the points about the same level? They look sort of to me, but my depth perception is actually quite bad. OK, so is that about equal? OK, one, two, three. Simultaneous. OK, so there you have choice C.

So now the interesting consequence of that-- so what that shows is that drag, in this case, is proportional to area. Now, it turns out that that's not always the case. So drag very often-- well, not very often in everyday life.

But very easily, drag can be proportional to size. And you don't know ahead of time which one it's going to be. So it turns out at slow speeds, low Reynolds number, this is true. Turns out at high Reynolds number, this is true. And this is the simplest experiment to show that.

So what this shows is that drag is proportional to area. So that with the same velocity, the extra weight is balanced by the extra drag force by exactly 4 to 1. And what that shows, now-- the consequence-- is that-- I'm going to replace the proportional with a twiddle. So it has an area in it. So I'm just going to get something with the correct units now.

So it has an area in it. And now you have left to play with density, speed, and viscosity. So now let's actually construct the drag force as a result of that. So we know by the experiment it's proportional to area. And now among these-- so this here is the kinematic viscosity, which is the one you may be more familiar with divided by rho, the density.

So we have to put some of these guys in, some of these guys in, and some of these guys in, and make the units come out as a force. Well, one of them we can do right away. There's how many powers of mass over on this side? In a force-- just one. And there's none here, yet. So we need to get one power of mass on this side.

Now, among all these guys, which of them have mass in them? Not this one,

because you divided out. Not velocity. Only density, and density has one power of mass. So you have to put one density. Question.

AUDIENCE: I don't know what the units of drag are.

PROFESSOR: So this is a force. Good question. So drag as a force. So this is just newtons or mass, length per time squared.

Does that help? So it's just newtons, in SI units. Or in general, mass length per time squared, so a mass times an acceleration.

So now, we've matched the units of mass. But we haven't matched the units of time yet. So let's sort out the time.

There's no time here. There's no time there. There's t to the minus 2 there.

Well, what can we do about that? We have to throw in some v and some ν . And the problem is we don't know how much. So the time doesn't help us enough.

Turns out to make the time and the length work, the simultaneous constraint, the only way to do it is that. You make the same argument to get the masses to match, the lengths to match, and the times to match. This is the only way to do it. So you don't have any viscosity.

So actually, that's the simplest experiment I know to show that the drag at high speed-- in other words, most flows are actually high speed, high Reynolds number-- is independent of viscosity. So it's ρav^2 . And that is a great result, because it tells you all kinds of stuff about everyday flows in everyday life.

Like for example, why did people reduce the speed limit on the highway back in the '70s to preserve gas? Well, on the highway, you're burning gasoline to fight drag. So if you reduce the speed, you reduce the drag, you reduce the amount of gasoline.

So in particular, if you reduce the speed by 20%, you reduce v^2 by 40%, which reduces the drag by 40%. So you just decreased the gas consumption by

about 40%. So you can see all these things right away just from this simple formula, which is an immediate consequence of this experiment.

Now, it turns out this-- how do you get that to work? This is the low Reynolds number limit. You can't deduce it from this experiment. But if you know that this is true, you can make the same argument and figure out how the drag force varies for low Reynolds numbers.

OK, so now let's just check whether this formula here that we've deduced works at all. So the follow-up question is the following, which is that I have-- one, two, three, four. Here on this side, I have four small cones. They're all identical to this small cone. So I have one small cone, two small cones, three small cones, four small cones.

So I'm going to stack all four small cones into a thick small cone. I'm going to race it against one small cone. So the question is, what's the ratio of these guys' terminal speeds? So let's call it v_4 and v_1 . So v_4 --

OK, so what is the ratio of their terminal speeds? $1/4$, $1/2$, 1, 2, or 4. So talk to your neighbor for just a minute. I'll take a quick vote. We will do the experiment.

OK, so let's take a vote. And then we'll do the experiment. $1/4$ -- no votes for $1/4$ ratio. Who votes for $1/2$? 1? 2? That's about 35. 4? About 10.

So let's do the experiment. One, two, three, four of them. OK, so now let me drop them like that. Well, it's kind of hard to tell it, isn't it?

So that was actually not a well-designed experiment, because you have to actually get out a timer and decide which one is going faster and measure how long they took. It would be nice if we had a way that was just like the other experiment. What was nice about the other experiment is when I dropped them, you got the answer by the fact that they hit simultaneously.

So if we could make them hit simultaneously, then that would be nice. Now, what do I have to do to do that? Well, I have to switch their heights 4 to 1 or 2 to 1. So let's

try 4 to 1. OK. Is that sort of 4 to 1?

AUDIENCE: No.

PROFESSOR: No? What do I have to do?

AUDIENCE: That has to [? go-- ?]

PROFESSOR: This guy's got to go down. Yeah, see, this is where my depth perception really fails me. So I only have monocular vision. I can see with both eyes, but I don't binocular fuse, so I can't tell depth.

AUDIENCE: Lower them both.

AUDIENCE: [INAUDIBLE]

PROFESSOR: Oh, that's true.

AUDIENCE: [INAUDIBLE]

AUDIENCE: Lower them both.

AUDIENCE: --corner of the desk.

PROFESSOR: Pardon?

AUDIENCE: If you go in the corner of the desk, then you drop one on the desk and the other one [INAUDIBLE].

PROFESSOR: Oh, but then you wouldn't be able to see it so well. So I want to do it on the desk just so everyone can see. OK, so if I lower them both like this, is that about right?

AUDIENCE: Yeah. [INAUDIBLE]

PROFESSOR: Lower? Wow. OK. OK. One, two, three, go. No, not very simultaneous. So let's try 2 to 1.

OK, I'll overcompensate in my mind. [? And it's ?] probably about 2 to 1. Is that about 2 to 1? This one?

AUDIENCE: [INAUDIBLE]

PROFESSOR: [? Socks. ?] Every time. OK, 1, one thousand, 2, one thousand, 3, one thousand. Simultaneous. And what's always amazing to me is I always listen to the class every time I do this. And I never believe them when they say it's really 2 to 1 in height. And I was like, OK, I'll trust you guys. And it always comes out simultaneous. So people haven't lied to me yet.

So 2 to 1-- why 2? Well, it had 4 times the weight. Same surface area, same density-- you couldn't change the air. So you have to change the v .

How much do you change the v by? Factor of 2, because you square it. And you make up for the weight increase by factor of 4. So factor of 2. So there you have an application of it.

So now, let me get to your question about what do you do if someone tries to spoil the experiment. So the first thing to do is-- well, let me say what were my reactions as soon as you did that. So my first reaction was, god damn, why did he do that? That was a really nasty thing to do.

But then the second reaction is-- whoop. So now I've developed a habit, which is a good habit to learn, of just pausing before you react to things. Because you're much less likely to cause bad interactions if you pause.

So I paused to myself. And I thought, there's actually no point in saying how annoyed I am right there. And this will happen. Suppose someone tries to wreck your experiment. You will be annoyed.

So it doesn't help you to actually say how annoyed you are and really make that person feel terrible. Because then what you've done is you've polarized the audience against yourself besides making that person feel bad. So it's much better to do what I did, which was say, OK, tell you what. I'll answer your question later.

But also what I tried to do is answer it implicitly. I don't know if you noticed, but what

I did was when I came to ask people, I figured, OK, so people sort of have an idea that it should be C just because of somebody said, well, I've seen the demonstration before. But what I wanted to know was not why you think C is right but why you think any of them could be plausible. So that was always part of the question, but I emphasized that part more.

And it has a good educational purpose, which is that you're trying to predict not just what the quote "right answer" is, but you're trying to expand your repertoire of options. So you're actually making yourself more creative by thinking, what could be plausible? Because it's that way of thinking that you're able to use in other problems.

So I tried to turn it around a bit and push it in a direction that it would still be a useful discussion for people. OK, maybe not as useful as if people didn't know ahead of time that the answer is C, but still a useful one. Does that help answer your question?

OK, so now what we've done-- we've actually gone through a whole teaching example. Yes, question.

AUDIENCE: So [INAUDIBLE] talk about when you're writing down the number of votes, if you should leave them actually like [INAUDIBLE].

PROFESSOR: I didn't see. That's a good point.

AUDIENCE: And so that way, those people would be like, oh my God you didn't see me.

PROFESSOR: This is a good point. And I didn't. And partly, it's because the lighting in this room is ghastly. Partly my eyes are not very good.

But all of those reasons support exactly what you said, which is that, especially if you have a few people in the class, you can always get away with adding one. And another thing you can do is you can always add one for yourself. You think, well, I actually have a plausible reason for one of these. Well, I'm going to vote for one of them.

And every once in a while, you vote for a correct answer-- you know, one out of five times. So the class learns. But generally, you vote sort of randomly just to give support to the various answers.

So you're right. The question was, is it better to not use zip ever? And generally, it's true. Unless you're dead sure no one voted for anything. And it's hard to see in a large class.

That's one of the advantages of the clickers. There's disadvantages and advantages of clickers. And we can talk about them. But you're right. One way to mitigate that-- just throw in an extra vote. Other questions?

So as I promised, what we're going to do with this example is now-- because this is actually not an aerodynamics class. You may be surprised to find out now. So you may have thought the purpose was to actually learn the air resistance formula.

If you do learn that, that's really useful. And I'd be really happy, because it's a great result which is very, very, very hard to derive in pretty much any other way. You certainly can't derive it from scratch from the Navier-Stokes equations. At least no one with current mathematical knowledge knows how to do that. So experiment really is one of the main ways of doing that. So it's a great result for that.

But what I want to use it for is deconstructing it, looking at the way it was taught and why all the things were done that way. So in that discussion will come out general principles that we'll use throughout the semester in all of our examples of how to do teaching, like for example, how to make a lecture, how to design a course. So as always, those principles are not very effective if I just say, well, here are the principles, and we're going to use them. It's much better if we actually try them out in example and see where did they show up by constructing them.

So the question for the next portion of this session is to identify all of the teaching elements in this. So for example, what's a teaching element? Well, for example, there was a vote or there was a second vote. So just deconstruct it to as fine a granularity as seems reasonable, and say, OK, this was done, or this happened.

And then, why?

So two questions-- do a two-column table. What and why? And there'll be a pretty long list because there was quite a lot of things done.

So find a neighbor or two again. We'll discuss the what and why. And then I'll clump the whys into principles. So any questions about that question?

ANNOUNCER: Due to technical difficulties, the rest of lecture one is unavailable. What follows is a summary of the material presented in the remaining part of the lecture.

PROFESSOR: Think back to the question about the cones-- which fell faster, or were they the same speed, the big cone or the small cone, and how that question was asked. What were all the elements in the way the question was asked? What was discussed? What did you do?

So it was scripted very carefully. And there were reasons for the elements of the script. So we've had a chance to think about that. And let me list many of these scripting elements and their reasons for them.

So on the left side, I'll list the elements. For example, there was lots of interaction. You were talking to each other. You were asking questions.

In fact, you weren't just asking questions. You were voting. So twice you voted. So voting twice, discussing.

So what are the reasons for that? What are the educational principles behind designing a question that allows lots of interaction, voting, discussing? Well, first of all-- the why-- it gives the teacher, it gives me, an idea of how the class is thinking.

If, for example, I ask a question, and in the first vote almost everyone gets it right, I know, OK, everyone pretty much understands this idea or this concept. I can spend very little extra time on it and move on to something that may be more confusing or more problematic. Whereas if most people get it wrong, I know, OK, either the book was confusing or what I explained already was confusing. And we need to spend more time discussing the core idea here.

So it gives me instant feedback about where the class is. I don't have to wait till the end of the term to find out on the final exam, oh, no one understood that. I know right there when I have a chance to do something about it.

The voting also has another benefit. So the first benefit is it tells me. Also, it makes this students form a public commitment.

And that public commitment has a strong benefit, which is that the students become much more involved in learning what the outcome of the discussion is. Because they've actually made a public commitment to one choice or another choice. So it increases the level of engagement.

Similarly, it creates tension. People want to know what's going to happen. So when the demonstration is actually done-- the final decider is the experiment-- everyone is paying very, very close attention. So I'll say not just tension, but I'll say it creates dramatic tension.

Furthermore, the chance for lots of interaction increases the amount of interaction in the whole class. For example, students will ask questions much more easily if they've already had a chance to discuss their ideas in small groups. So that's one set of elements and the educational reasons for building those in to how one asks questions in class.

Another one is that I used a physical object, in an actual demonstration, so these cones. And the physical object is also cheap. Anyone can make those. You just cut circles out of paper, cut a quarter away, and tape it together. You have a cone.

What are the benefits of that? Well, first, it's much more convincing than if I just do a derivation from the Navier-Stokes equations or however one gets to the result. And say, OK, well, therefore the drag is proportional to the square of the speed. Or therefore, they all fall at the same speed whatever their size. If I just say that, or even if I prove it with equations, that's not nearly as convincing as seeing it actually happen.

And that's where in terms of being convincing, it's also important that the demonstration be cheap. If, for example, to see it actually happen requires \$100,000 of equipment-- well, who knows what happens in that \$100,000 of equipment and sensors and test devices and whatnot. Whereas if it's a cheap piece of paper you can cut out for \$0.02, well, then anyone can try it themselves, too.

And it's not so mediated by lots of sensory devices. It's much more immediate. It's much more convincing. So I'll say here in parentheses, a cheap physical object-- ideally, if possible.

Furthermore, the physical object actually connects the mathematical and physical and engineering ideas to the physical world. In the end, we want to try to understand how the world works, maybe put it back together in ways of our choosing. So purely living in the formal world, we're living in the clouds. By bringing in a physical object, we actually put our feet on the ground as well.

Another part of the demonstration of the script was various things that might have seemed extraneous. For example, I mentioned that I hope my socks were matched well when I stood on the table. I also discussed-- when I was standing on the table, I said, OK, I need the class's help here because I don't have depth perception. So I can't tell when I'm dropping them-- when I was dropping one cone versus four cones, I can't tell when I've got this one twice as high as this one. And so you need to tell me. So I talked about my failing in the depth perception department.

So both of these might seem extraneous to engineering and science. But actually, they have a sound educational reason. So the socks joke-- well, that makes the teacher seem much more human.

Similarly, for the lack of depth perception-- oh, well, the teacher has flaws, too. They're not this perfect person who seems to know everything. And in fact, that one, specifically because I didn't have depth perception, I needed the help of the class. So that, again, is an excuse to involve the whole class. So no depth perception makes a teacher human is also an excuse for more engagement.

And related to discussing another element of the script, I want to amplify this one up there, the discussing. And I'll put it back down here. The discussion happened first by yourself, then in a small group, and then in the whole class together where people were suggesting reasons. So I'll say discussions at several scales-- self, group, and class.

So what's the educational purpose of that? Well, I mentioned one purpose up there, which is it increases questions. And that's certainly true.

Another one is by allowing people to think for themselves first, you're giving space for what's called the introverts. Some people like lots of time to think for themselves, and only then do they want to share with other people. Because otherwise, their thoughts get derailed by what everybody else is saying.

Some people don't know what they're thinking till they talk to other people. Let's call them the extroverts. So by allowing space for self talk and group talk, you're teaching to the introverts and the extroverts. So you're matching to the learning styles of different students in the class.

And then by scaling it up slowly from self to group to class, you make it safe. You make it not a huge transition to start to go to the next stage. Whereas if I just ask the question of the class, OK, whole class, now, you tell me what you think about this question and I skipped these parts, only the usual suspects would be offering me ideas here. The people who always raise their hand-- maybe they sit in the front row.

Whereas by allowing people to think for themselves, then discuss in a group the ideas that they thought for themselves, check out what they've done there. If they still think they don't understand something and no one in the group understood it, then they feel safe asking the whole class. We're actually building a bridge for people to participate in the large group.

So again, that point's up there. But it's so important I'm putting it down here, too. So I'll call it builds a bridge to collective participation. And that participation can be

people contributing ideas or questions which are themselves ideas.

Another feature of how the whole thing was done was that I walked around a fair amount. I used a lot of the space. For example, even some of the vertical space, standing on the table. Moving over here, moving over there to make sure I heard the question from that side of the class. So filling the lecture space.

Well, what's the educational reason for that? Well, in a way it's the opposite of the socks joke. In one way, it's the opposite. In another way, it's the same. It's showing that the teacher is human and that teaching is a human activity.

This is what actors do on stage. The stage, the whole stage is there for a reason. And the actors will use all of it. They won't just stand in the middle the whole time, except for rare comedy monologues or monologues.

But otherwise, all the pieces of the stage are there for a reason. And the actors use it. They make that space their own space. They fill the lecture room space.

So as a teacher, you want to do that because that shows that this is your space. You're comfortable there. And it increases your credibility with the students.

And similar to this, it brings in students from all parts of the classroom, especially if it's a big classroom. They all feel somehow connected to what's going on. Because you haven't just stood in one corner of the room or just paid attention to one section of the class.

So in one way, it's the opposite of the socks joke. Because in that way, the teacher is being a bit self-deprecating. Here, the lecturer is acting very confident by filling the space.

But in another way, it's the same. They're both playing on the human part of teaching, which is inescapable. And if it's neglected, the teaching falls flat.

And finally, there was one other point which may seem like a mechanical point. But it's so useful that I'll put it here, too. And I'll write it with big chalk. Point is, I wrote everything on the board using big chalk.

And why is that important? Well, in a small classroom of maybe 10 or 15 people, it probably doesn't matter. Everyone can read everything. But if it's at all a large classroom, people can't read the writing way in the back. By using big chalk, you increase the signal to noise ratio.

Now, that may not seem so important when you first think about. The reason being is that you already know what you're writing. So even if you see really thin lines, something that's not very clearly written, you still know what it should say. And you just read it correctly.

But the students, on the other hand-- they don't have the knowledge that you have. So they can't error-correct any-- fill in the missing gaps in the lines. They need as much signal as possible to really copy down anything correctly, to make sure that they're not adding noise onto the signal that you're trying to get across.

So in some ways, a small point, but in other ways, an important point. Because if you don't do it, you'll throw away most of your other benefits because the students will actually be incorporating wrong information, just errors, just by mistake without even realizing. And the big chalk can actually minimize that.

So just a mechanical point. I always keep pieces of big chalk in my backpack. And wherever I happen to be teaching, I can always pull them out and use them. Because you will find many classrooms only have standard chalk provided. And the big chalk is something you have to do yourself. So just carry a few pieces with you as you need.

So those are some of the many scripting elements in this example. And you'll see a similar example in a subsequent lecture, in the lecture on teaching interactively, which is lecture six. And you'll see some of these points come up again and some of these reasons discussed again in a different example.

So you'll have two different engineering examples, but done in a similar way. And you can see the scripting elements and how they're different and how they're the

same in both examples. And see which ones you can use in your own teaching.

So now, from these scripting elements, we've extracted teaching principles. So credibility, signal to noise ratio-- just remember those. And then here's a bunch more.

I want to summarize them, extract the main highlights from that so that you can come away with a clean picture of what to watch for throughout this semester. So the main themes of all of these are-- I would say they fall into three categories. Let me list them. And then I'll break them into three categories.

There's ways to promote questions and discussion. There's using stories and humor. And demos and, related to that, things you can see-- visual examples.

And another pair of environments-- credibility-- filling the lecture space-- and what I haven't directly said yet as such, but we'll call it a safe environment for learning. Creating a safe environment for learning. That's what discussion at several scales enables. You create a safe environment for people to think for themselves, which then makes it safe for them to think in a group and discuss in group, which then makes it safe for them to think in a whole class.

And so that makes safe bridge, or two bridges, towards collective participation. So you've made a safe learning and questioning environment. Without this environment, that won't happen.

So I put these in three columns because I think they fall into sort of three pieces of the brain. Questions and discussion-- sort of left brain. Stories, humor, demos, and visual-- that's right brain. And credibility and a safe environment-- I'll call that the emotional brain, the amygdala.

Maybe you could put humor over there, as well. But the reason I put preamble stories with the right brain is it's a different kind of learning than we think of when we think of left-brain learning, for example, learning an analytical method or the sequence of steps or a recipe. The learning that happens from stories-- for example, about the depth perception-- is a different kind. It's kind of implicit in a

way, more perceptive and the holistic. So I put it in the right-brain category.

So these are main themes in creating your own classroom teaching environment and structuring how you're going to teach. And sure, there's also all the questions of content. But the reason I'm focusing on all of these is that the questions of content-- those have been done so many, so many times. You can find all the content in a gazillion different textbooks.

But the question is, how do you integrate all of that content into something that makes for good student learning? And to do that, you need to take account of all this, all of these features, all these aspects of the brain. Because humans are not computers. And they can't just learn by being programmed.

So from all these themes, extract one giant theme, which is that teaching is not necessarily equal to learning. Just standing up there and teaching stuff is no guarantee that students will learn it. You need to pay attention to all these features, all of the human interaction to make sure that learning actually happens.

So that's, if anything, the main theme. Or phrased another way is that meaning and knowledge must be constructed by the learner. And all these ideas up here, these scripting elements, these principles here are ways to help that construction happen. Just telling them doesn't do it. You have to enable, facilitate, that construction.

So what we're going to do for the rest of the semester is we're going to see these principles, these principles, these boiled-down themes, this idea, this large idea-- the big idea of the entire course exemplified in several topics and areas that are central to teaching science and engineering and mathematics at the college level.

And so the outline for the rest of the semester is as follows. Today was lecture one. And that was general principles of teaching.

The next one will be on how to teach equations. Equations are central in all science and mathematics and engineering teaching. So how do you teach equations-- in other words, some of the central content-- taking account of all of these ideas?

Can you tell stories when you teach equations? How can you do that? Well, we'll see.

The third lecture, the third topic, is taking account of students' misconceptions and thereby avoiding rote learning. So you can see already where some of the ideas that we've been talking about here are going to help here. For example, having lots of interaction and voting-- you find out where the students are.

You'll find out if they have funny ways of thinking about stuff, maybe even predictable ways, but ways that don't help them actually solve problems in the real world. Well, how do you take account of that? There's one way right there already.

Then designing homework and exam problems. And the fifth one is course design. How do you structure a whole course?

Sixth one is teaching interactively. As an example, you've already seen one example, which is this kind of question. Well, what are the general principles behind such questions? Can you make longer versions, shorter ones? Are there short ways of building in interaction and questions into learning?

Then what do you actually do when you come into the classroom? Lecture planning and performing-- how do you plan one lecture? So this is the overall structure of the whole course. How do you plan and perform one lecture?

Topic eight is teaching with blackboards and slides. So what are the advantages, generally speaking, of blackboards? But what are situations where slides are actually a really helpful way to teach? Slides meaning-- well, it could be old-style photographic slides, but pre-prepared PDF files that projected on the screen with an LCD projector is generally how it's done now. And then how do you plan blackboard work? How do you construct slides so that they're effective in creating learning?

Ninth is sort of a result of all these. Well, if you're going to apply all these principles, you'll find yourself wanting to change a lot about how the course is done or how it was done previously. Well, what are the barriers to that?

In particular, what are the political barriers to educational change? So that by being aware of the barriers, you're more able to go around them, surmount them, take account of them, plan for doing it bit by bit by bit. But eventually, hopefully designing courses in ways that you think are good for promoting learning.

And then the 10th topic will be a summary of everything, using the examples we've done the whole semester and a chance for-- well, you'd ask questions about the whole course. OK, so that's the themes of this entire semester of teaching college-level science and engineering one topic at a time. See everyone next week.

ANNOUNCER: Answers from lecture two to questions generated in lecture one.

PROFESSOR: What I'm going to do is answer your questions from last time on the feedback sheets. And I'll pass out a new set of feedback sheets in a moment. So I should say that the questions were, as always, excellent. And I learned a lot by thinking about them.

And I hope that you'll learn a lot as you hear the results of everyone else's questions together, and that they reflect concerns that maybe all of you had at different levels and the question that you may have put down may not have been all of your concerns. But collectively, hopefully it captures most of them.

So I'll categorize the first section of questions as in reality. I've typed in all the questions. I'm going to put them all on the course website. So you can see the questions. And the answers will be here, but you'll see the questions.

So in reality-- one question along that line is, what about grading? How do you actually implement your grading policy as an assistant professor in a traditional department? So my grading policy is generally that, especially in a pass/fail course, that the grading be very minimal. And in general, I think that's a good policy for grading overall. And we can talk throughout the semester about why and the research behind that.

But how would you do that if you're starting out new? And the general rule is there's no right answer. For example, one solution-- it's not quite the answer to the

question-- is to take a position at a place where you're the department head.

So actually, I was offered a teaching position like that after I finished graduate school. And I thought long and hard about it. So I would have been the head of the physics and math department.

Now, that was the good side. The bad side was that I was the only member of both departments. And so on the one hand, I was a department head. But also, I was the only one doing all the teaching. And I would have only me to boss around.

But in that situation, you do have a huge amount of freedom. And I could have done pretty much whatever I wanted. Now, I decided not to take that position because I really wasn't sure exactly what I wanted to do in terms of improving teaching. And I thought, well, I really need some more experience. And I decided to do a post-doc.

But that is one solution to that problem. It's not a very generalizable solution. There are not many positions like that.

Another solution is to what I call the Clark Kent solution. So you go around as a traditional faculty member, in the Clark Kent outfit. And then as soon as you get tenure, boom, off comes the suit. And everyone realizes that oh, actually, we hired someone else completely, who actually has all these interesting ideas about teaching.

So that is generally legally protected to some extent. And you won't easily be fired, although a colleague of mine in Canada-- the university is trying to fire him for giving all As in a course. So this does speak to this question. And it shows it is a tricky issue.

So he believes-- and I agree with him-- that grades generally just produce obedient people. One of their main functions is to produce obedient people and obedient students, rather than students who love learning and want to question. So he wanted to teach one of his courses-- he's a tenured professor of physics. He wanted to teach one of his courses pass/fail.

And the university said, no. By university regulations, that course is graded only. It has to be taught with grades.

So he said, OK, fine. On the first day of class, he just told everyone they were going to get an A+. And according to the TA-- at least, this was then reported in Canada's *Globe and Mail*, their sort of *New York Times*-- one of the teaching assistants for the course said, yeah, there were a few students who took advantage of that fact. But most actually did more work and were very interested in the material because of it. So I would say, basically, the thing was a success.

And that's generally what I find, that the less emphasis you put on grades-- especially at a place like MIT-- the students' natural interest in the material comes out. And they're more and more willing to work and learn. And that produces long-lasting learning. Because they're doing it for their own reasons, not because you stood over them with a grade and beat them over the head.

So that was good. The bad part is the university basically said, well, you're defying us, and you're going against the purpose of the university. It's not really clear what the purpose of the university is, except maybe to produce obedient people. So they said, we're going to institute proceedings for your dismissal, to strip you of your tenure and fire you, which is a big step for a tenured professor.

And meanwhile, they banned him from campus. So he's now not allowed on his own university campus. So then he came to campus for a film screening, because he runs a film series on the campus.

So he came for that, and the university police arrested him. So he was arrested for going to his own university. So then it got into the national press in Canada, which doesn't make the university look so good.

But that's all by way of saying that grading is a very touchy issue with universities. And it's really not clear what to do about it, because it's so embedded in the system. So I can't really offer you any solutions to that question except to say that it's a very tricky negotiation and you want to plan your activities carefully.

If you're going to use a lighter grading system, don't do it all at once. Get people around you to accept it slowly, slowly. Get students on your side slowly. Do things slowly.

Don't make any sudden moves that get yourself fired. Work with other people of like minds. Work together collectively. So it's not a long-term instant solution.

But any kind of social problem-- and I think grading is a social problem-- doesn't have any instant solutions. So I wanted to answer that one first, to basically tell you that I don't have all the answers to all the questions. And I want to give you honest answers as far as I know them.

OK, next question about reality. You've obviously done this many times before. As someone who needs to figure out a logical order for the material in addition to balancing preparation time and research, how do we juggle all this in addition to simply focusing on style?

So I want to dispel one misconception was that last time, I wasn't saying that you can substitute style for preparation and really knowing the material. It's really that I wanted to up the importance that people give to what people would call style by saying that the way you present, how you present, is as important as what you present. In fact, it is, to some extent, what you present.

If, for example, you're very interested in the material, and you present it in that way, well, the students are very naturally going to become interested in the material. As a test of this, you can actually do little home experiments on this principle. So just go around to somebody. You can do these little like *Candid Camera* experiments. Just go up to them and smile, just like this, and then watch what they do. And a whole bunch of people actually just smiled back at me for no reason at all, just because I smiled.

Now, not no reason at all. It's because we're social creatures. We're programmed from millions of years of evolution to pick up other people's emotions and ways of being. So if you're enthusiastic about the material, if you're interested in it, and you

present it like it's important, well, that actually gets transmitted very effectively and picked up at the other end very effectively. So actually, that is part of the content.

So I wouldn't say style is separate from the content. How you present, how you think about the material is a crucially important part of the material. Because that's when students are going to be taking away. And that's going to be affecting how they think about the material.

So it's not just focusing on style-- that sort of gives it too little importance. Instead, yeah, how do you think about all those issues as well as surviving your research grant? And again, there I would say the way to do it is to start slow. When you're an assistant professor, you need to focus on your research to get tenure. So focus on your research and just try small teaching experiments bit by bit. Maybe in your first year, just try putting in one small conceptual question per lecture or per week.

And if that goes OK, maybe try longer ones. Try more the next semester or the next year. So just try small things. And as they work, grow them. So that's one way, so you don't have to sacrifice your research and hose yourself.

So preparation time, as well-- so try to borrow notes from colleagues. Try to get as much from other people as you can share. Talent invents, genius steals. So steal all the good stuff around you.

So another one is how does this work in the real world, which is basically the same thing. So what I'm trying to do in this class is show you general principles that you can use always to guide yourself in as far as you want to go in your teaching. So now how far you go in your particular situation depends on your situation and how much importance you put on doing new teaching methods, new experiments right then. But I'm not saying you have to start everything tomorrow, like the first day you're a TA, all of sudden throw out all the regular stuff and do everything like I'm demonstrating now. I'm showing you this as examples to illustrate principles for directions you could go and for threads you can pick up as you see best.

Syllabus and logistics for this class-- any exams or problem sets? Yeah, there's

problem sets, which you've seen one already. No exams. And so how are you being evaluated? Basically again, very light touch. Basically, just make a reasonable effort on the problem sets, and you'll be fine.

I'm hoping basically that the material's interesting enough that you don't need a stick beating you, saying, oh, you must do this, you must do that, you must do this. It's not a required course. People are taking it really because they're interested. So I'm not going to try to ruin that with a whole bunch of grading sticks.

Does it matter which subject number we're assigned for? No, and I don't even remember what the subject numbers are. I know 595, and there's a whole bunch of them. So I just write et cetera. No, it doesn't matter, as far as I know.

Could we have a break after one hour? Yeah, I think that's a good idea. So I'll give everyone like a two- or three-minute break at the hour just so you can stand and get your blood flowing again.

Biology examples-- can we have biology examples? A fair point-- so actually, today our first example of equations is a biology example, amazingly.

OK, so now, interactive teaching-- how do you teach a class interactively if you have a lot of material to get through? This is a very interesting question. It comes up quite often. And the answer is that you don't get through it in the lecture.

So the lecture is a terrible place to get through lots of material. In fact, even the word "get through," "cover"-- those all have the wrong sense to them. And so Victor Weisskopf, MIT physics professor for many years, he said-- and I think it's a great saying-- instead of covering a lot of material, I prefer to uncover a few key ideas.

So uncover is the right verb. Cover has the sense of smother. You can't see it anymore. And that is what happens when you cover too much material. You want to uncover a few ideas and let them bloom.

So a lecture is something that's paced at human scale. You talk at maybe 150 words a minute. People can't write that fast. They can write maybe 15 words a

minute.

Reading is much faster. Reading-- people can read 300, maybe 400 words a minute. So if you have lots of material to get through, don't fall into the trap of putting it all on the blackboard or on the overhead slides.

And we'll talk about that in the session on making good slides and using the blackboard. You want key ideas to be there. And you can leave lots of the details for reading. So that's one answer.

The other answer is that sometimes, actually, I think one of the fundamental problems with so much teaching is that we try to cover too much material. And one of the goals should be for good teaching is to reduce how much material one covers. And there's a simple estimation argument to show why that's important.

The estimation argument is that basically, suppose you cover 100% of the material. But because it's so much material, students remember only 10%, and really learn only 10%, which I think is actually a reasonable estimate. Because they're just so overloaded. They have no time to make connections, and it just flitters away. So 10% is all they retain.

Well, you could cover, say, half the material. And let's say that they still don't remember everything, even though you've done half. Maybe they remember half of that, because they have time to struggle with it, make connections. So now, they're at half of half, which is 25% retention instead of 10%.

So that's a plausible model. I'm not claiming those figures are actually based on exact research or anything. But just a plausible model for how reducing the amount of stuff you cover can actually increase learning. So try to reduce material when possible. Almost always, there's too much material.

OK, so again, how do you pace lectures? If you do too many demos and you have less material, advanced students might get bored. Actually, I find advanced students are actually quite interested in demos and questions like this that we used last time. They want to really understand what's going on. And it's those kind of questions that

help them.

Covering lots of material-- again, they can read it in a book much faster than you can write it on the board. So put it there.

Can these principles be applied to upper-level graduate classes? For sure. You can apply them all the way from kindergarten through graduate school because they're really based on how people think. And they're based on common ways that people perceive the world and reason.

And that doesn't change-- I mean, life does change when you become a graduate student. But your whole way of looking at the world doesn't change that much.

So how do you deal with classes where someone dominates a discussion or the class does not like to participate? Sort of two ends of the same coin. So what I like to do is if someone keeps trying to say stuff, I just say, oh, well, actually I want everybody to participate. Could I hear from someone I haven't heard from? Just with a light touch. You don't have to make a big confrontation in class about it.

If people don't like to participate-- for example, suppose you ask them to discuss with each other and they don't. So here's a trick I learned actually from one of the teaching seminars when I was in England, which is that you just turn your back. And why do you do that? Well, your back is not as interesting as your front.

So students are actually taught with, say, 12 years of teaching to watch the teacher, watch the teacher. So one of the reluctances to talk to each other is they're watching the teacher, figuring out what the teacher's saying and doing. Kind of like Clever Hans was watching his trainer-- do I do more clips on my foot? Is that 42? 6 times 7-- OK.

So students are actually taught, basically, after 12 years of conditioning, do that very automatically. So you just have to break that conditioning a bit. If you just turn around, there's nothing really that interesting to look at, unless you're maybe-- I don't know, some fashion model or a GQ model, which I'm not claiming to be. So then the students will just naturally be more likely to talk to each other. So you

create the conditions for that.

Another one-- and I often use this trick, because it's actually not a trick-- is sometimes I'm thirsty. I just walk out of the room and go get a drink of water. So if it's an interesting enough question, the students will be talking to each other about it. And there's definitely not you around there, watching them or worrying them, for them to focus on. So that's one very useful trick.

Generally, though, the overall point is if the class doesn't want to participate, you just make it more and more safe to participate. You make sure you never criticize people if they say something that wasn't right. You make sure you value the wrong answers and you explain why. So all of the things I talked about last time about safety means you just have to do them double if people aren't participating.

How do you cope with a variety of confidence levels among students? Also interesting. So there, I find actually that most students aren't very confident. They have different levels-- they're all generally much lower than you think. So they do have some different levels, but it's generally overall lower than you think. So I spend more of my effort making sure everyone feels comfortable.

But again, if some students are much more confident than others, I try to mix up the level of questions that I ask. I ask some questions that I know most people are not going to be able to answer and some questions that I know most people will answer, just so everyone has something. And then on the problem sets as well-- warm-up problems, regular problems, really hard problems.

Like in Donald Knuth's textbooks, the fifth set of, kind of, problem at the end of the chapters is unsolved research problems. And you never know. Someone might actually solve one of them. So you can put something for everyone in there.

What about the left brain? Surely humor and demos can't take you all the way. Yeah, and that's true. And so my answer to what about the left brain is that the left brain is what basically most teaching has focused on for most people's experience over the last 15 or 16 years.

So I'm not saying, forget about the left brain. I'm saying that you basically already know how to do the left-brain side of teaching. You have so many models of that. It is pretty much what we think of as teaching. You go up to the blackboard, and you write down a series of symbols one after another, write down a series of equations.

So you already have models for that. And we'll talk about how to improve those. But I'm not so worried about that part. What I'm worried about is the neglected part.

So this you could think of as the balance. And then you'll be able to find ways of integrating the left brain. And we'll do left-brain things, equations. But how do you integrate that with all the quote "right brain," the humor and the demos?

How do you project confidence? Fake it till you make it? Yeah, that's basically right. So one way is to actually make sure your voice is clear. So to do that, my piano teacher in graduate school-- actually, she was a voice teacher, as well. She gave me a really useful exercise, which is-- I do this for like 30 seconds before I come to lecture.

So the exercise is you first just close your lips. And you mmm, you hum. So we'll all do this together. So you hum until you can feel it vibrating in your nose. That's step one. So let's all do that together. [HUMMING]

And if you have hay fever, you can tell if you're doing it right in the spring. Because you'll dislodge pollen grains and you'll probably sneeze. That's what I find in the spring. When I do that, I actually start sneezing. My theory is that I'm dislodging pollen grains and then I'm sneezing as a result of them.

So mmm-- so now you've got a resonance up here. And now what you want to do is with the same mmm sound, now do it in the back of your teeth with your mouth closed. So you feel behind your teeth.

So we'll do step one and then step two. Mmm and then the teeth. Mmm, teeth. [HUMMING] And you should feel in your lips vibrating, kind of tickling. OK, so that's step two.

Step three is to then make the vowel sound that is most likely to make your mouth resonate and be really wide and open. That's E. So we'll go hmm and then mmm and eee. OK, so nose-- [HUMMING] lips-- [HUMMING] eeeeeee.

OK, that's step three. And then the final step is you just add some words. You modulate it with words. All right, so I'll give you a demonstration. Then we'll do all of it together. [HUMMING] Eeeee-- (SPEAKING ON SAME NOTE) how are youuuuuu.

OK, so now, that sounds a bit strange. But you find after you do that, your voice is much more resonant. Actually, I can hear it right now. To my own ears, my voice sounds much more resonant and clear.

So let's do that. [HUMMING] Eeeee-- (SPEAKING ON SAME NOTE) how are youuuuuu. So you'll find, actually, what you've done is you've shifted your voice from here, where it just makes your throat tight, to the front. And just by doing that, you will project. And by projecting, you actually sound more confident. And you'll feel more confident.

So that's one way. But another way is to be confident of your material. And another way is, as you said in the question, just fake it till you make it.

Now, there's a few more questions. I'll answer some of them on the website. But I wanted to answer one more. How long did it take you to become such a good teacher?

So I'm glad people think I'm a good teacher, or at least one person thinks so. But there's a general answer to that question, which is actually going to be one of the topics today, which is, how do you become an expert in anything? And the first example I'm going to show you-- it's biology equations. I'm going to use that.

And then after that, when I talk about expertise in general, not just in teaching, and where that comes from. And I'll show you the results of some studies. And then I'll come back to that question. And I'll hopefully answer it then.

So those are I would say 2/3 of the questions. The ones I haven't answered I'll try to

answer online. And I'll pass out these in just a moment.

But right now, what we're going to do is we're going to do the first example of equations, which is from biology. Now, before I do that, any questions that have occurred to you meanwhile? Did I create any new questions? Yes.

AUDIENCE: Very germane, but if this is P/D/F, are we supposed to be registered as P/D/F?

PROFESSOR: I think it's automatic. I don't think there's any way not to register as P/D/F.

AUDIENCE: OK, thank you.

PROFESSOR: So the question was, if this is pass/fail, do you have to specifically register as that? I don't think so. I think it's automatic. So yeah, basically, don't worry about your grades. Everyone's going to P.