MIKE SHORT: OK, guys. Welcome to the first filmed and hands-on installation of 22.01, Introduction to Ionizing Radiation. I'm Mike Short. I'm the department's undergrad coordinator. I'm also your 22.01 instructor. But I also want to introduce you to Amelia Trainer in the back, who one of the three TAs for the course. She took it last year. Everything is still very fresh in your head, I bet.

AUDIENCE: More or less.

MIKE SHORT: Cool. So she'll be-- she and Ka-Yen Yau and Caitlin Fisher will be with us all throughout the term. So if there's something that you don't like my explanation for, you've got three people who just took the course, and struggled through my own explanations, and can say it in a different way.

So let's start off by taking your knowledge of physics from the roughly 1800s education of the GIRs, the a General Institute Requirements, up till 1932 when the neutron was discovered. And I would argue that this particle is what makes us nuclear engineers. It's the basis behind reactors. It's what differentiates us from the high energy physics folks and everything, because we've studied these and use them quite a lot.

And so we want to retrace Chadwick's steps in discovering the neutron. And this is the only time you're ever going to see me have a bunch of words on a slide. It's not a presentation technique I like, but this paper is awesome in the clarity and expressiveness of him saying I ran this experiment and found something unknown. I'll use basic conservation of energy and things you learned in 8.01 and 8.02 to prove that it has to be a neutron, that a neutron must exist.

It's elegant and brilliant, and I want to walk you guys through it. Did any of you get a chance to read the Chadwick article yet? OK. I'll show you where that is, because hopefully by now you're all aware that we have a learning module site. It's where I'm going to post everything. It's where you're going to submit everything for the class. But I'll save to the end of this class to go through the actual syllabus because I want to get into the physics.

So let's bring your knowledge from classical mechanics and E&M up till about 1895 when Wilhelm Roentgen used X-rays and used them to, well, image something for the first time ever. Showing the contrast between bone and tissue, he was able to illuminate the bones in a hand. And then about a year later, the X-rays got a whole lot better.

So by then, it was known that there were high-energy photons that had differential contrast between different types of material. A year later, after the nicer X-ray, J.J. Thompson conclusively proved that there is an electron by taking these cathode rays, as they were called at one point, and sending them through two charged plates. And he was able to show a slight deflection.

So these cathode rays, as they pass through an electric field, change direction a little bit. And from the change in direction, you may not know the mass or the charge, but you can get the mass to charge ratio. Because if you guys remember from 8.02, from electricity and magnetism, as a charged particle passes through an electric field, it's deflected. And the amount of that deflection, or the curvature, is based on the mass to charge ratio. So Chadwick knew that electrons existed. This was a known thing, as well as alpha, beta, and gamma rays. So the electrons that came out of the nucleus were later renamed beta rays.

And at around the same time, Ernest Rutherford and Paul Villard, working in Canada and France, discovered that there are some heavy charge particles that have very little penetrating power, while Paul Villard discovered that there are some other radiations-- I think he called it produced by disintegration of nuclei-- that have very high penetrating power. And they named them alpha, beta, gamma in order of their penetrating power or their range.

And so it was later figured out that these were also high-energy photons. So this is something to note is that gamma rays, x-rays, light, whatever, it's all photons. However, once this pops back up, gamma rays emanate from the nucleus. So when we refer to a gamma ray, we mean a photon that came out of a nuclear interaction or a nuclear disintegration, not an electron transition. So this is one-- this is what makes a gamma ray a gamma ray, is where it comes from. Otherwise it's a photon. It behaves just like any photons.

So what did Chadwick see in 1932? This is the first one-page article that he sent out to *Nature* to say, I found something weird. So he found out that when you take alpha particles from polonium-- so let's say we had a source of polonium sending off alpha particles, which I haven't told you what they are yet. It emits a radiation of great penetrating power when it hits a foil of beryllium.

And it was not known what these things were. So in goes the alphas to beryllium. Something happens, and something comes streaming out that couldn't be explained by current theories. It was also noticed that when hydrogen was placed in front of it, when a piece of hydrogen in the form of wax, which contains a lot of hydrogen, was put in front of it, the amount of ionization increased, as measured by what's called an ionization chamber and an oscillograph, nothing more than an almost-sealed chamber, a piston with some charge on it that would then deflect. As it were to pick up positive or negative charges, it would move inwards or outwards and send an electrical signal to something like an oscilloscope. So this was a way that you could figure out how many ions were created by this highly penetrating radiation interacting in the ionization chamber.

And they estimated that with the old theories, if this highly penetrating thing were a photon or a gamma ray, it would have to have an energy of 50 times 10 to the 6 electron volts, or 50 MeV. He said, OK. Well, if that's to be basically the experimental observation, say, a 50 MeV photon must be responsible for the ionizations that we saw.

And so again, this is what the experiment looks like where you've got a polonium source naturally emitting alpha rays. They hit a foil, a beryllium. They produce what he did not know at the time was neutrons. We actually do know that beryllium produces neutrons pretty well. Beryllium is an interesting neutron multiplier. It undergoes what's called an n 2n reaction where one neutron comes in, two neutrons can come out, and it transmutes into something else.

And we'll go over what this notation means, what these nuclear reactions mean. If you don't understand it, don't worry. The whole point of today is to open up questions that we'll spend the rest of the semester closing and answering. So again, if you're lost, don't worry. It's the first day of class, and it's your first day of Modern Physics. So not to worry.

And this is an actual picture of what it looked like in the paper, a simple polonium source on a disk that was made by the natural decomposition of radium into polonium, a piece of beryllium, a vacuum chamber. Because it was already known that the alpha particles coming from polonium have an extremely short range. We're going to figure out why as part of this class. But without that vacuum there, the alpha particles wouldn't make it to the beryllium. So that much was known.

What wasn't known was why are we getting so many ionizations. They attributed it to what they called a process similar to the Compton effect. To tell you what that is, in 1923, Arthur Compton figured out, among other things, Compton scattering, where a photon can strike an electron. The photon changes energy. The electron picks up some energy.

They exit at very well-known angles, and they transfer very well-known amounts of energy. So this is how they knew how much energy the photon, if it were to exist, should have. And they said the process was analogous to Compton scattering because they said in this case, a proton would be ejected. It would take a lot of energy to eject a proton using a photon.

And Chadwick saw this and said, well, if we ascribe this phenomenon to a Compton recoil, we should see about 10,000 ions. We actually saw about 30,000. So there was more ionization going on than can be explained by what's going on. In addition, those protons should have a range in air of about 1.3 millimeters, and they saw much more. So this is something simple-- theory and experiment don't match. There's got to be a different theoretical explanation if the experiment was correct.

And so finally, what I love-- the last sentence in this-- the quantum hypothesis-- a quantum was the way they referred to a photon. It was called a quantum back then, a little packet of energy. Can only be upheld if we forget about conservation of energy and momentum.

Now, I'll ask you guys from 8.01 to 8.02. So Sean, when can you throw out energy and momentum conservation?

AUDIENCE: [INAUDIBLE]

MIKE SHORT: That's pretty much right. You can't. A situation probably wasn't given to you where you can just throw away conservation of momentum and energy. In fact, nature gives us three quantities that we can measure and conserve-- mass, momentum, and energy. And throughout this course, if something is not conserved, you've probably got the math or the physics wrong.

So this is something to remember throughout the course and our derivations and in your problem sets, is conserve mass, conserve momentum, conserve energy, just like what was taught in 8.01 and 8.02. So I'll call your answer correct. You don't remember a situation because, well, it didn't exist.

And that's what Chadwick noted. He said theory and experiment don't work unless we throw out conservation of energy and momentum. Whether this was a kind of passive-aggressive thing to say-- well, this clearly can't exist-- or he was suggesting maybe it doesn't work, I don't know. I wasn't there.

But later on, about a year later, he published a follow-on paper confirming the existence of a neutron by reconciling these differences in theory and experiment. So he restated what he saw before. This was the first paragraph of it. And again, it said that radiation excited in beryllium. Whatever happened after the alpha particle came out. It had a highly penetrating radiation, distinctly greater than that of any gamma radiation found from radioactive elements. Something is different.

And I want us to take a sec to digest this. This is the part I actually want you guys to read, so take a minute and read through some of this stuff. And then we'll begin explaining his argument. Let me know when you guys are done reading.

OK. I see some folks starting to look down. So let's take this apart and figure out what was Chadwick saying. He was saying that if a quantum was responsible for this energy, a photon, then we can write a nuclear reaction. I'll write it in the notation that we use now, which would be beryllium-9, the only naturally occurring isotope of beryllium, plus an alpha particle would lead to carbon-13 plus a gamma ray. And that gamma ray would take away the energy from this reaction.

So now we can start to figure out, is energy conserved? Could this gamma ray actually exist? And if it does, does it account for the ionizations that Chadwick saw? So for each of these isotopes, we know a few different quantities. We know what's called its rest mass energy, which is this. It's rest mass times speed of light squared.

This should look familiar to everyone. I've seen it on t-shirts all over campus. And it may take two or three weeks to really wrap your head around what Einstein's equation really means. It is that mass and energy are equivalent. You can express mass in terms of energy, and vise versa. And you will be doing so to conserve energy and mass in nuclear reactions, one of which is written right here.

So if each of these things has a given rest mass energy, let's say a rest mass energy of beryllium and a rest mass energy of an alpha particle, and this alpha particle maybe had some kinetic energy-- it was moving pretty fast, so we'll give that the symbol t for kinetic energy, because that's what you're going to see in your notes and in the reading and everywhere. And then this carbon-13 nucleus has got to have a rest mass and a kinetic energy, and then this gamma ray, it's going to have some e gamma energy.

Now, the question is, is the mass and energy conserved in this equation? What we're actually starting to write is what's called the q equation, or the universal mass and energy balance for any kind of nuclear reaction. So let's say we have a large initial nucleus i and some small particle i moving at it with some great speed. And after some reaction occurs, you have a small, final particle leaving and a different, large final particle leaving. They don't necessarily have to be the same.

Let's give these particles designations 1, 2, 3, and 4. In the end, we should be able to write the difference in either total energy or total mass of the system as this value q. q is, let's say, the amount of energy that turns into mass, or vise versa. So let's say energy transfer.

And so if we start writing some mass conservation equation, we can say that the mass of nucleus 1 plus the mass of nucleus 2 should equal the mass of nucleus 3 plus the mass of nucleus 4 plus however much energy from nuclei 1 and 2 turned into energy into 3 and 4. We could also write the same thing for their kinetic energies. In this case, the finals are on the end. So I'm sorry. I should use t for kinetic energy.

So what this is saying is that if some mass has turned into energy at the end, that energy had to come from somewhere. It had to come from the initial kinetic energy or conversion of mass to energy from this reaction. And so notice that now, you can actually express the masses of the nuclei in terms of their energy, of their initial and final kinetic energies. And this right here is what we're going to be spending the first two or three weeks deriving, using, and exploring in order to balance nuclear reactions and explain why they are the way they are.

So let's make sure-- we'll keep this nuclear reaction up here, because Chadwick proposed a different one to explain what he saw. And some of the evidence for this was that he put some aluminum foil in between the beryllium where things were being liberated and the ionization chamber and oscilloscope, or oscillograph, as he liked to call it. And that way, by putting more and more pieces of foil in there, you can deduce what's called the range, or the distance that the radiation will travel before it stops by losing energy through a whole host of different processes that we'll be working through together.

If this were to be ascribed to a proton, then it should have had a certain range in air by this curve b right here. Instead, he found this curve a where things moved about three times farther than could have been explained if that were a proton to be liberated by all this stuff. So he's saying, OK, something has got more penetrating power.

We know now that part of the reason for this is if there's a neutron, and there's no charge on it, then it's not going to interact with the electrons in matter. It won't even see them. Whereas protons or any other charged particles will see the electrons in matter and will interact with the electrons and the nuclei. So a little flash forward to say, we can explain this pretty simply with what we generally know. But this was the first time somebody had to come up with [INAUDIBLE] explanation, and it was quite hard.

And so moving on, he can say, well, I know what protons should be injected from paraffin. I know a formula to describe what quantum or photon energy had to create them. And then instead, he says-- this is where his major hypothesis is-- either we relinquish conservation of energy or neutron or adopt another hypothesis. And this was already put forth by Rutherford back in the '20s that there may be a neutron, but there wasn't any proof.

And this is what provided the proof. He gave an alternate nuclear reaction if there were to be a neutron which had roughly the mass of a proton. Then let's write a second one down here. I'm going to erase these extra notation, and we'll write the competing nuclear action below. And he said that-- let's say we start with beryllium-9 plus an alpha particle could instead become carbon-12 and a neutron.

So I'd like to ask you guys right now to work this out. Are both of these reactions balanced in terms of mass? Are there the same number of protons, neutrons, and electrons at either side? And just to let you know, an alpha particle is better known as a helium nucleus. So that means that there's two protons. There's four protons plus neutrons, and beryllium-9 has four protons and nine protons plus neutrons. And carbon-12 has six protons. A neutron has zero protons.

So in each of these-- and I'll fill in the other ones here. So that's a 4, 4, 2, and 6. Do we have the same number of protons and neutrons on both sides of both equations? I see a number of heads and one person saying yes, we do. So both of these reactions are balanced in terms of mass. The next thing to do is balance them in terms of energy.

Now, they can both be balanced in terms of energy because you could attribute the change in the amount of mass from here to there and attribute that to the energy of the photon. That's when you'd have to have a photon of energy around 50 MeV. But if a proton-- I'm sorry-- a photon of energy around 50 MeV can't explain what we saw. Instead, if there is something like a neutron which also has its own rest mass and its own kinetic energy, and that neutron were highly penetrating, it could explain what Chadwick saw.

And so the masses and things of these nuclei were fairly well known back then to, well, six significant digits based on some very careful experimentation. And all he did is say, all right. Let's take all of the energies in this reaction. Remember how I told you over here, you can write any nuclear reaction in terms of its kinetic energies, and the difference will give you the q value, which you can attribute to the conversion of mass to energy?

That's what Chadwick did right here. He took the full reaction, saying here's the mass of beryllium, the mass of the alpha particle, the kinetic energy of the alpha particle. Note that he assumed that the kinetic energy of beryllium was zero. It was just sitting at room temperature. Does anyone know the approximate kinetic energy of atoms at room temperature? Order of magnitude, even?

It's around 1/100 to 1/1,000 of an EV, or an electron volt. So when we're talking about beryllium, whose kinetic energy, we'll say, is around 0.01 EV, and the alpha particle whose kinetic energy was around 4 times 10 to the 6th EV, you can see why it's neglected. And you can do that too. You do not have to account for the initial kinetic energy of a nucleus at rest. This is the first approximation that we tend to make to the q equation to just have fewer variables. And don't worry if you don't remember this now, because we have a whole lecture on the q equation.

And so finally, he said, all right. We'll subtract all the masses. We're left with the kinetic energies and a little bit of excess rest mass. That's got to be-- this has got to exist. And so this inequality has to be satisfied, which indeed it was. Using this inequality, he said that the velocity of the neutron has to be less than its kinetic energy if it had all of that energy, 3.9 times 10 to the 9 centimeter per second. Indeed it was lower-- not by that much, but it still satisfied this criterion. So things are checking out. That's pretty cool.

He looked at another nuclear reaction that was known at the time. If you were to bombard boron-11 with helium, you end up with nitrogen-14 and either-- either end up with nitrogen-15 and a photon or nitrogen-14 and a neutron, explaining another reaction that wasn't as well known before. So I'd like to write this nuclear reaction, because I want you all to get very familiar with writing nuclear reactions.

Let's say boron-11 plus an alpha particle-- we'll say it has a mass of 4-- becomes nitrogen 14 and a neutron. We also have a shorthand of writing this nuclear reaction which I'll use on the board for speed's sake. Usually if you put the initial nucleus and the initial incoming radiation, comma, the exiting radiation, and the final nucleus, these two right here are equivalent. This is just a shorthand for nuclear reactions.

This is what you'll tend to see because it's a lot easier to write this shorthand and parse it visually than it is to parse a whole nuclear reaction. So I just want you to know if you don't know what these are, just remember to stick the arrow here, stick plus signs in for the parentheses, and you've got the same thing.

And using these, you should be able to very quickly determine is this reaction balanced. What's actually going on? And there will be tabulated values of q values or energy amounts for these sorts of reactions in all sorts of tables I'll be showing you.

And so finally, he figured out what the energy or the mass defect of the neutrons should be. Does anyone know what a mass defect is? This is another core concept. Let's say you were to want to make an atom of helium. So you would have to take two protons whose masses are very well known, and two neutrons, and bring them together.

So if you were to have-- let's say the initial mass would be 2 times the mass of a neutron plus 2 times the mass of a proton. And the final mass is just the mass of a helium nucleus. You'll actually find that the initial mass does not equal the final mass. In bringing nuclei or nucleons together, they actually release what's called their binding energy. It's what keeps the nucleus bound together.

There's a little bit of mass turned into energy. And so you know how we like say the whole is usually more than the sum of its parts? In nuclear engineering, the whole is a little less than the sum of its parts. It definitely is not equal.

And Chadwick was proposing that a neutron should actually be made up of a proton and an electron in very close proximity. And since the masses of the proton and the electron were known, he said, well, if we bring the proton and electron very close together to have an overall neutral neutron particle, it should have roughly that mass defect or that difference between the energy of its constituent nucleons and the energy of the assembled nucleus.

And you'll hear the words "mass defect" and "binding energy" used. Mass defect is in terms of mass in either-- you can give it in kilograms or in atomic mass units, or AMU, or in, let's say, MeV c squared. And you'll also hear of the binding energy just given in things like MeV.

I want to show you where you can find these things now. I'll give you the single most useful website that you'll be referring to. And I've posted it up on the Learning Module site, so now is a good time for me to show you that the site exists. And let me just clone my screen real quick. It's a wireless HDMI thing, so it takes a sec to pop back up.

Great. Has anyone not been to the site yet? It's OK. You don't have to be embarrassed. OK. About half of you. I recommend tonight that you start looking through the site. One, make sure that you can log in, because you'll need to log in to see some of the copyrighted materials that I've posted, and two, because this is where you'll be posting all your homeworks, getting the assignments, checking due dates. Especially if I postpone a problem set, I'll put out an announcement and post it here. So this is the place to look for everything.

And in addition, I've posted a lot of useful materials for you guys. They're all at the bottom, and the top one is the [INAUDIBLE] table of nuclides. Anyone seen this kind of thing before? We have posters of it down on all the first-floor classrooms in Building 24. This is our go-to chart. When you want to find out all of the nuclear half-life, radioactive decay and decay of energy, probability of certain direction, whatever, this is where you go.

So let's take a look at, well, helium-4 since we've been talking about it, better known as an alpha particle. And you'll notice a few different quantities visible. The atomic mass, 4.0026032 AMU. And this is another tip I want to give you guys right now. Don't round these numbers. That's one of the major trip up points. If you say that's approximately 4 or 4.003, you probably won't get the p-set questions right, because 1/1,000 of an AMU can still represent almost an MeV of lost energy.

So let's say you have a nuclear reaction that liberates a 1 mega electron volt or one MeV gamma ray, and you get the fourth digit wrong in one of your mass calculations. It's like that gamma ray didn't exist, and you won't get the answer right. So again, word to the wise-- do not round.

You'll also see what's known as the excess mass or the binding energy. So this binding energy right here, if you were to take two protons and two neutrons and bring them together and look at the difference in masses from, let's say, the same old formula as before, you would get a difference of 28,295 keV, or about 28.295673 MeV. Again, don't round. Let's figure this out right here.

So we have 28.295673 MeV. And there is a conversion factor that you should either memorize or write down. Either way, it's good. It's about 931.49 MeV per atomic mass unit. This is your mass energy equivalence that you'll be using over and over and over again. And again, don't round. Those last two digits are important.

So by taking this energy and dividing by this conversion factor, you can figure out how many atomic mass units are lost in terms of actual mass when you assemble an alpha particle from its constituent pieces. And the rest of the stuff we will get into later. It's not really relevant to today's discussion, but it's definitely relevant to today's course. Cool. OK.

And then on to-- one of the last things that he mentioned is some predictions to say, OK, let's say this neutron exists. It doesn't have charge. Most matter interacts with other matter by virtue of Coulombic or charge interactions. If the neutron has no charge, it shouldn't really see matter except for nuclei.

This is exactly what he said, is an electrical field of a neutron will be extremely small except at small distances, because he proposed that a neutron is a proton plus an electron. So once you get to around the radius of the neutron, you might start to see some charge, but not before. And so most other matter, unless you have a head-on collision with a nucleus, neutrons won't see it. And that helps explain why the neutrons had such high penetrating power or high range-- because they just went streaming through most materials, invisible to the electrons. So very forward thinking, and turned out to be very correct.

And then finally, as a kind of mic drop conclusion, came up with the final concluding statements. OK, we know there's a neutron. We know its mass. The actual mass of the neutron is about 1.0087 AMU so within 0.1% of Chadwick's calculations and predictions based on 1930s equipment, which is strikingly awesome. And there you have it. That's the discovery of the neutron using most of the concepts that we're going to be teaching you here in 22.01.

So right now, I'd say your scientific knowledge, if we don't count what you read on the news, is roughly around 1850 when all the E&M stuff was being figured out. We are going to bring you screaming into the 1930s. And by about month 1, we'll hit the present day when we can start to talk about the super heavy elements like the ones that were discovered last year. I think there was even some this year.

But we'll look at the *Physics Today* article from last year to get to the point of explaining why super heavy elements might be stable. Why are we even looking for them? Where do cosmic rays come from? How do we know that they're cosmic rays and not something else? How can you tell a reactor turns on anywhere in the world by measuring different bits of radiation, which is an active defense project that folks are pursuing right now? Lots of really fun questions.

And speaking of questions, do you guys have any questions about what we've explained here, how we've retraced Chadwick's discovery of the neutron from basic nuclear science principles? So who here has seen these nuclear reactions before? Cool. This is something that I hope folks would cover in high school. But with a general trend of watering down science education, I didn't want to make any assumptions.

I'm glad to hear this was covered. Was this coveted at MIT? Are you guys relying on high school knowledge? OK, good. Not good. Good I know where you are. Not good that MIT doesn't teach anything nuclear until year two. That's OK. You guys, along with the Physics Department, will get at least a 20th-century knowledge of physics and 21st by the end of month 1.

So I want to come back to the Stellar site, and specifically the syllabus. I've taken a lot of care to write a very detailed syllabus of what we're going to do, what I expect of you guys, what you can expect of me, and what we'll be doing every single day. So if you want to know what we're going to be doing, if you have a class that you miss, and you want to know what notes you're going to miss, it's all written up here.

I want to get right into assignments, because everyone wants to know what am I responsible for. Well, not too much-- nine problems sets, three quizzes. The final exam is just a quiz. It's only worth 24% of your grade instead of 20 to get the math to work out, because I eliminated one problem set to avoid running afoul of MIT regulations, but not assigning things at the last week of class. But there are three quizzes, so the final exam is just another quiz. It's not a super high-stress, crazy thing, because I don't see a point in doing that.

You can make your assignments however you want. I don't care as long as I can read them. But I do ask that in the end, you submit a PDF file on the Stellar site. And the reason for this is my first course that I ever taught at MIT as a professor were the graduate modules, 22.13, Intro to Nuclear Systems, and 22.14, Intro to Nuclear Materials. I accepted paper submissions.

And by week 3, I had to microwave them. Because three or four times, I definitely saw blood. And there were also some weird stains that I didn't want to explain. So I added the habit of unstapling, microwaving, and re-stapling the p-sets before grading. So in the digital world, it's sterile. I'm not a germophobe. I just don't like blood in my house, especially if it's not mine. So I ask that you guys submit PDFs on the Stellar site.

They're due at 5:00 PM to make sure that you're done and you can go home and relax or work on something else. I used to some have things due at midnight, and I had every submission was 11:59 PM. I'm not going to do that anymore. Do make sure to submit 15 minutes early. So if your computer or the Stellar site has trouble, send me an email or a text or whatever saying, I'm trying to submit, and it's not working. Here is a backup, or I'm leaving something under your door. And if you want my cell phone number, that's also my office number. It's also my only number. It's in the MIT directory. So if there is some emergency you need to make me aware of, please do communicate. I'd rather you tell me than be worried about not telling me and then find out later. So are we all clear on that?

As far as what the assignments are, each assignment is going to be about 50% basic calculations, working out things like these to make sure you've mastered the material, that you understand writing nuclear reactions, you can balance a q equation, you can tell me about what your cancer risk would be from a certain dose of material. So this is like when you go out in the real world, the sort of calculations everyone would expect you as a nuclear engineer to be able to do.

And then 50% of each problem set is either going to be analytical questions of considerable difficulty. This is MIT. We're not just here to give you the basics so that you can regurgitate a textbook onto the first person who asks. We're here to make sure that you can go farther. Because you guys are the future of this very small and diminishing field at the moment if you look at the nuclear power in the US. I would say growing in terms of the world, but not in terms of the US. And you guys are going to be in charge of leading this field and determining where it's going to go. So you've got to be up at the cutting edge, and we're going to take you to the edge of your abilities.

My favorite kind of problem is to give one sentence for the question, five or 10 pages for the answer if you don't get the trick. Now, that's OK. It's perfectly fine not to figure out the answer in the end. In fact, I'll usually give you the answer for the analytical questions because I want to see your approach. I'm not interested in you nailing the answer. I'm interested in seeing how you think. And copious partial credit will be given for the way you think.

So if you have a missing step, and you say, I don't know the step, I'm going to assume variable a and keep going, you will get credit for the subsequent steps. I want to see how you think from start to finish and how you cover for holes that you can't get through. So everyone clear on that? Partial credit, yes. Use it to your fullest ability.

The other half of the problem sets will have take-home laboratory assignments. It's not just enough for me to tell you about nuclear engineering. You have to see it for yourself, and you have to feel it for yourself. And once in a while, you'll get a mild electric shock by yourself if things go wrong, but that's OK. It happens to the best of us.

I got zapped by our-- you guys have all made Geiger counters, right? Has anyone not made a Geiger counter yet? Oh, OK. It sounds like we need to run another workshop. Well, our Geiger counters rely on a neat little boost converter power supply that takes 9 volts and steps it up to 400 volts via some switching things. That means you have 400 volts on a big metal tube. And if you're working on your circuit and you happen to brush against it, you get zero current, so it doesn't hurt you in the medical sense, but it hurts.

I also have a dance I call the 60 Hertz shuffle. It's the high speed shaking that you do when you're connected to 60 Hertz somewhere from the wall outlet. None of you guys will be exposed to this, but I've done it enough times that I have a name for the dance. If you get 400 volts, you'll just kind of scream. And I don't care how manly men you guys are. Everyone makes the same pitch scream with 400 volts. We're all equal in the eyes of electricity.

For these laboratory questions, I'm going to ask you to both complete an assignment where you'll, for example, measure the half-life of uranium, measure the radioactivity of one banana, confirm or refute the linear no threshold hypothesis of the dose. And the experiment itself won't take that long, but I want you to write it up in proper documented format using these sections. So I'm going to be teaching you guys how to write scientific articles.

So actually, this is kind of a good time to ask you guys. How would you define the word "science?" Luke, what do you think?

AUDIENCE: It's a process of getting knowledge by fitting theories to empirical evidence.

MIKE SHORT: Gaining knowledge by fitting theories to empirical evidence. OK. So I hear knowledge gaining by some sort of well-justified and accepted means, right? Monica, what do you think?

AUDIENCE: Science is the study of the natural world through patterns and mathematics, I suppose.

MIKE SHORT: Cool, yeah. Let's say the studying, modeling, and abstraction of the natural world into ways we can understand. Jared, what would you say?

AUDIENCE: Which one?

MIKE SHORT: Oh, there's two Jareds. I want to hear both, and then I'll-- yeah.

AUDIENCE: Science is-- I'd probably go with it's the same thing Luke said, gaining knowledge through experimentation and trial.

MIKE SHORT: Cool. And other Jared?

AUDIENCE: I think what Luke said about fitting theories to empirical evidence and testing them that way.

MIKE SHORT: OK, cool. I like these. And these are the generally accepted theories and descriptions I've heard of science. And I want to pose a question to you guys.

If a tree falls in the woods and nobody is around to hear it, can it win the Nobel Prize? It's kind of an expression. So if somebody discovered the neutron, and they wrote up their findings, and proved that it exists, and they put it in their desk, and the house burned down, and the person died, was the neutron discovered? What does discovered mean?

So to me, science is equal parts everything you guys said and communication. If you discover something and you don't tell anyone, the information technically doesn't exist. It dies with you. And you don't want that to happen. So I want to make sure that you guys both understand the science and understand the importance of communicating it effectively to people. Because that's the other thing you're going to be doing as leaders in this field is explaining things.

You better believe when Fukushima happened-- I was a postdoc at the time. I was not a person, I guess, in the academic sense. People here treated me very well, but I was also very aware that I was not one of the greats. Still I am not old enough yet.

I was getting calls all day, all night from news agencies saying, you're at MIT. I saw your name on the directory. Do a radio interview and tell us all if we're going to die. And you can only imagine what the professors on this hall were dealing with. So folks were traveling around, answering things left and right.

I ended up doing some weird podcast on a Brazilian news channel that I don't think ever got aired and stopped doing it after that. You as undergrads even might be called if somebody wants to know something. And so it's best that you not only know the material, but you can convey it effectively, briefly, and in a way that your audience can understand.

The audience for these articles is any undergraduate in any engineering program anywhere. That's your lowest common denominator-- not to say that that's a bad thing, but it is the audience that you want to aim your writing at. So what I want you to be able to do is say what you did, why you did it, and what it means.

In communication terms, this means a less-than-100-word abstract, a very brief synopsis of what you did and why it's important. That's the teaser. This is the trailer to make somebody read what you actually did and see why they care. This is the main method and currency through which scientists communicate is articles of this type.

An introduction and background which says why are we studying this problem. And the answer is not because I told you to, and your grade depends on it. I want you to think about why this problem is important, and put it into context, and give any of the scientific background to understand what's going to come next, like the experimental section. Describe what you did in nitty gritty scientific detail. This is usually the easy part.

I put this gamma ray in this bucket, and it made this color, and I made this noise, whatever. A results section where you show all of your data and a discussion section-- notice that these are different. You want to separate your actual results from your interpretation of your results, because someone else may have a very different interpretation of results-- for example, Chadwick.

Somebody found that beryllium bombarded by alpha particles emitted radiation of great penetrating power. That's the result. The interpretation or discussion said it's probably a Compton-like effect from a photon. By separating your results and your discussion, you allow people to mentally say, OK, I get your results. I believe that you found these numbers. I have a different explanation. And you all may have different explanations for what you see in your own labs, because you're also probably going to get different results.

And then finally, a conclusion where you quickly re-summarize your major contributions. Your abstract is the teaser. Your conclusion is like your re-abstract with the context that people now believe-- or don't-- what you did.

And think about how you guys read articles. So who here has read scientific articles before? More than half of you. Let's see. Alex, what do you read first?

AUDIENCE: If it's a journal, probably the abstract. But given that I'm mostly interested in the topic, I tend to go to the conclusion section.

MIKE SHORT: That's right. OK. I'm glad you said that. That was my next question. You read the abstract. The next thing you read is the conclusion. The next thing you usually read is you skim through the results and the figures and see if it's worth looking at. Then if you're like, OK, this is worth my time, then you slog through and read everything to make sure you understand it all.

So when you're writing these articles, think about who's reading them and how they read them. Because if you guys don't tend to read an article from top to bottom, neither will your audience. And that's true. Most scientists skim things because we have a lot to read. So that's OK.

And I am very interested in you guys completely documenting your experiment. Pictures are also awesome to use. Accuracy of results and analysis-- so did you round when you weren't supposed to? Did you have a clear numerical typo that you can't explain? And the readability of the report-- I want you to spend time making this readable.

I expect that this part of the assignment will take roughly five hours, whereas the basic questions will take roughly three to four hours depending on how well you're doing. And that leaves three hours of class time and a couple hours for whatever else happens in life, let's call it.

Since you've never written these before-- wait a minute. I shouldn't say that. Who's written these kinds of things before? Anyone here wrote a scientific article? Two. OK, three. Cool. So most of you haven't, and that's where I assumed you'd all be.

We have a whole lab dedicated to scientific communication called the Comm Lab run by someone, who happens to be my wife, four doors down. We live and work next to each other. It's pretty cool. And you get an automatic three-day extension on the lab assignment if you go to the Comm Lab.

There are three reasons for this. One, I want you to get better grades, so I want you to learn how to communicate. Two, I don't want to spend time trying to figure out what you were trying to say. So better articles means less grading time for me. And three-- OK, let's just say it's two reasons. That's enough.

And for everything except for the quizzes, it's perfectly OK to work together as long as you attribute who did what, you write your own articles, don't Xerox anything, and say who took the data. So if the whole class wants to get together and take one set of data and work for that, fine. If you all want to do the labs yourselves, which I highly recommend, fine.

But I'm not going to tell you how to do the lab assignment in this, as long as you say what you did. And I want all of you, if you haven't yet, to head to integrity.mit.edu to see our official policies on what is considered plagiarism, what is considered working together, what's considered academic honesty.

I will assume, because it's on the syllabus and I'm telling you now, that you've all read this, and that there will be no cheating. It's just not something that's part of my job description, and I don't want to deal with it, which means I won't deal with it, which means the consequences will be severe. So I don't think I'll have to worry about that.

And then for the late policy, it's just 10% of the value of assignment for each calendar day, not each business day. So if you're running really late and you haven't started an assignment the day it's due, better to take the 10% penalty and do really well than hand in nothing on time. So keep in mind how can you maximize the points in this course. I'd rather you hand in something good late than terrible on time. So if you really need that extra day if MIT gets crazy, take it. 10% of a problem set is 0.4 points on your grade. It's not that big a deal.

Then as far as the syllabus, I want to show you very quickly. We've got when things are due. I'm going to change these dates to basically just shift them all forward by one day to account for the new Tuesday, Thursday classes. So I've got when the problem sets are due. And Friday is recitation activities.

If there aren't too many questions on a particular Friday, I have a lot of fun stuff in store for you. For example, tomorrow we're going to be talking about radiation utilizing technology, including plasma sputter coders, one of which we have set up in my lab, and I'd like to show you. Because it's a way that you can coat materials and other materials, and you have to generate this beautiful, glowing purple plasma in order to do so. So you ionize nitrogen. You induce sputtering, which is a radiation damage process which we'll be going over, to coat things in other things.

There will be once in a while where I have to shift a class into recitation because I'll be at Westinghouse or in Russia. And I think that's only twice during the whole year. So you won't miss any classes. We'll just use the recitation time.

And then other, times we'll be doing measuring the radioactivity of banana hashes. Or once we talk about electron interactions, we're going to go use a scanning electron microscope. The carrot at the end of the stick to make sure that you guys do well-- the top two people performing on the quizzes get to pilot and choose the samples for the SEM and elemental analysis and the focused ion beam demonstration. So you guys get to pilot something that's, let's say, as complicated as a space shuttle but deals with things much, much smaller.

So I'll put you in the driver's seat in the machines of our lab, and you get to bring whatever you want to analyze and find the elemental analysis of and use the world's smallest machining instrument that can cut 5-nanometer slices of things using processes that we're going to discuss in this class. So the better you do, the more you get to use it.

And at the end, we'll have a nice debate. I call it arguing with Greenpeace when we'll talk about-- now that you'll have known all of the nuclear science and engineering and can speak scientifically about topics, we're going to go after a lot of societal misconceptions. Do cell phones cause cancer? Does living near a nuclear power plant cause cancer?

Does arguing with Greenpeace cause cancer, whatever it's going to be? So I want to make sure that you're well-equipped and confident enough to go out there and hold your own in a vigorous debate with an angry, emotional environmentalist. You guys will be calm, peaceful, and informed environmentalists. After all, that's why a lot of us are here, is we want nuclear energy to happen because we care about the environment.

There's other people that don't want nuclear energy to happen because they care about the environment. To each their own, I guess, motivations. But I want to make sure you're well equipped to also tackle things like is food irradiation bad. That there's all sorts of websites with dancing babies and weird Geocities-like graphics saying food irradiation is evil. You won't find a lot of scientific articles if that's the case.

And to see if you'll put your, let's say, cancer risk where your mouth is, the last day of class, we'll have an irradiated fruit party where I'll be buying only the kinds of fruit that can be imported into the US because food irradiation is done. Otherwise, the USDA would not let it into the country. And this is mostly things like mangosteens from Thailand, pineapple from Costa Rica. And interestingly enough, Hawaii is considered a different country agriculturally. It is so far away that they have different agricultural pests. And without irradiation, we couldn't import some of the produce from Hawaii, because it could decimate some of the crops in the Continental US. Pretty crazy, huh?

Yeah. It's the-- what, it's the 49th state, but agriculturally, a different country. So it's about 5 till, so I'm going to stop here. And we will start with radiation-utilizing technology on Friday, tomorrow, downstairs in Room 24-121. And then we'll move over to my lab at 2 o'clock to see the plasma sputter coder.