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R. SCOTT KEMP: Welcome to 22.04 and 22.103. This is a typical class, but it-- let me just tell you a little bit about the history of this class. It started out as it's just like a small focus. Six students, and we were interested in exploring some of these questions about why nuclear power has struggled in the world.

The undergraduates petitioned the department to make it a mandatory class, which meant migrating obligation went way up. And then the department decided to create a graduate version of the class, which also then became mandatory thanks to student petitions.

So here we are. This class now is huge, and it's very strange. This class will challenge everything you believe, probably, about nuclear power for a reason.

We want you to know why you're doing what you're doing, and we want you to understand the debate about why nuclear energy has and will, in a way, struggled to thrive, at least in the United States, but also, if we're fair, increasingly struggling in other parts of the world, including places like France, Japan, Korea where nuclear power has historically, in recent years, had a heyday-- and of course, it had a heyday in the United States, too, but much farther back.

So that's the idea behind this class. It used to be there was lots and lots of reading in this class, and the kind of Haas-style class where there's hundreds pages a week of reading. But as the class grew and became mandatory, that became a little burdensome for a lot of students.

So there's still substantial reading, and we want you to do the reading, but that's kind of up to you-- oh my gosh. We are way over the number of students I anticipated. The syllabus-- current syllabus is posted on Canvas. The syllabus goes in chronological order, so if the readings are shown before the lecture, try to do those readings before the lecture. If the readings are shown after the lecture, you do the readings after the lecture.

There are-- so now let me talk about homework. So one of the goals of this class is to teach you how to write coherently and convincingly, which is a skill that is, of course, increasingly becoming lost as AI becomes our crutch for writing.

I would contend that even though AI can fix your writing, it would still be nice to be able to write and, more precisely, read what you-- read things critically. And so the goal-- one of the goals of this class is to do that. In fact, it's a core requirement for the undergrads. And it's not technically a core requirement for the grad students, but I will remind you that you will have to write-- if you're a PhD student-- you have to write a thesis no matter what. And if you're a PhD student, you also need to write a prospectus and defend your prospectus in front of the faculty.

For many of you, this will be your first chance to write about a nuclear topic and defend it with faculty review. It's a great opportunity to dry run that experience to help you pass calls. So that is part of the motivation for asking you to do a lot of writing.

The only writing that you absolutely must do in this class is the final paper. It is-- so I'll talk about the final paper in a moment, but to help you do your final paper more successfully, we have this idea that you can do these small writing assignments over the course of this semester in response to the readings-- or either directly in response or the subject of the readings, we'll see how they're structured. And those will be reviewed, you will get feedback on them, and then you would turn in a revised copy later in the week.

So historically I had a TA that would grade all these readings. You can see how much readings-- how many essays I would have to grade. It takes about, for a class of this size, about 35 hours of grading a week to handle all the essays. Since-- because of the Trump budget cuts, there are university budget cuts, and I now no longer have a TA for this class.

So in consultation with the department head and others, we have devised the following process to grade the readings. Your initial submissions would be submitted, if you opt into the homework, believe it or not, to an AI review that I have trained on a data set, and actually does a really good job, better than I can do, honestly, of finding logical errors in your arguments. AI is extremely good at textual analysis. For all the flaws, it can sometimes make with facts-- it's very good at textual analysis.

You would get an AI-generated response, and then you would have to write-- you would treat it like a little peer review that you would get if you submitted a journal article. You have to respond to all of the criticisms. So you would say, you've made some kind of logical fallacy error in this section, and then you can either fix it or you can say, I believe the review is incorrect, and write in your cover sheet to your submission why you're not going to change it, but you need to look at it.

As long as you go through that process, you turn it in, and I'm convinced that the final version has had your attention and is a meaningful thing, you get 100% score. Because the purpose is just to get you motivated to practice reading-writing-revising, reading-writing-revising, reading-writing-revising.

And so you would do that about seven times-ish over the course of the semester. The exact number will have to be adjusted because I have to revamp the syllabus to accommodate the capacity of the AI grading system, which is limited in exactly the kinds of writing responses it can respond to. So the final version will be looked at by me. But you just-- like, full credit, no credit, kind of response.

If all that sounds like a waste of your time, and you are really busy and you're taking 83 units, and you just don't want to deal with this, check the box that says, I want to opt out of homework, and you can just write the final paper. So it's up to you.

If you want to practice learning, do the homework. Total homework score is only going to be about 15% of your total grade, it's just there to give you a little bit of motivation. If you don't do your homework, you can't get an A, but if you miss an assignment because you've got to go to a conference or you're sick or whatever, 1/7 of 15% is 2% of your grade, it's not going to kill you. So that's the logic of that.

So if you want-- please check your box of choice. If you want some more time to think about it, go ahead, but please get that form back to me by Friday. And you can put-- if you're not going to fill it out now and leave it up here, you can put it in my mailbox on the second floor of Building 24. Or shoot me an email with your choice.

OK. Let me talk a little bit about the final paper. So the final paper is either-- the final paper includes a process of peer review, reviewing someone else's paper, and revised paper, and then I grade the final revised paper. Now AI has also changed how this was done.

In the past, that was it, you turn in the final paper and I would grade it. Now I get final papers and I can't tell what-- where the final paper-- I can't tell if you know anything or if this is generated by a computer.

So as a result, everyone in this class will have a one-on-one oral exam with me in the last week and a half. I will read your paper, I will put questions on the paper, you will meet with me, and I'll talk to you about it, and be quick and painless, and all we want to make sure is you know what you're talking about.

And if you know what you're talking about and I'm convinced you wrote the paper, then you get whatever score is on the paper. If I'm not convinced you know what you're talking about, we have a longer conversation. So that's how the final paper will be graded.

OK. So what should a good final paper look like? It's a research paper. It is not-- and I need to underscore this a thousand times, it is not a book report. Do not just summarize some topic in the literature and write it into a paper. You need to come up with an idea over the course of the semester, a question that you want to answer, and refine it to a point where you can go do a little bit of original research and answer your question.

And that is what your final paper is about. And that is really excellent practice for the qualifying exam for the graduate students. That is exactly what you need to do to write your prospectus. If you can't do that, if you're simply summarizing the field, you have not identified a research direction and you will not pass your exams. So this is your first practice at being able to actually identify an interesting and tractable question.

And we will have workshops where you meet with students and groups, and people will help you get to that point where your question is well-thought-out and tractable within the scope of what we can do in this class. So we'll give you lots help. There's also the Writing Lab in the department, which has been doing this for a long time and is very well-versed at helping people go through this process.

But I just-- if you leave it to the end and you're like, oh, I'm just going to write a review of the Westinghouse AP1000 about why all of its safety features, and you don't have a question, you're not going to get anything more than a C on that paper. So that is really important that you understand, this is a research paper.

There is a whole document on the syllabus, on this Canvas site called Guidelines for Writing Your Final Paper. Go read it. It tells you how to start, it tells you how to organize a research paper, it tells you the expectations and length. I think it tells you probably everything you need to know.

So I also have posted papers from previous students that got A-pluses on their papers. So you can look at their papers and be like, oh, OK, I get it, and it's pretty straightforward. They've all agreed to have their papers shared on Canvas with you guys. And if you aren't satisfied, I have a whole collection of people who have such papers and I can give you more.

And I will be very happy to meet with you throughout the course of the semester to help you refine your paper, to think through it if there's any challenges. OK. So any questions about the syllabus, the homework, or the final paper? All right. So that's kind of it for expectations. Let's talk about what you're going to see-- this is very thin. Yeah, question?

STUDENT: Will we have an opportunity to see what a homework assignment will look like before opting in or out of?

R. SCOTT KEMP: Yeah. So they're just prompts. And they're basically one-page essays. That's the expectation. You write a page. Most people find it hard to write a page. They want to write a page and a half or two pages. And the goal is, if you've written two pages, look at it again. What is here that I really don't need to say? And practice being concise, clear, take out extraneous stuff.

There are some-- yeah. So I can also give you some guidelines. If your paper in any place, just, like, well, in my opinion, this is how it should be, and you don't give arguments to back it up, then that's not a good response. I really-- you need to back up your responses. It needs to be like pointed and concise. That's what makes a good reading response. Yeah.

But remember, there's no A or B or C. If you do it, you go through the exercise, you get the critique, and you turn in the revised copy, you get 100%. So don't fret too much about that. It will teach you, as you go along, what you need to do. There was a question here? No? Yep.

STUDENT: Would you train the model using as a past assignments?

R. SCOTT KEMP: Yeah. Yeah. I used past reading responses. It's really good. It's amazing. I'm like, oh yeah, I didn't catch that. It's really good. It's also not your normal-- it's a very high token AI, so I think it's 100,000-token output or something. So it's an expensive model to run. Yeah?

STUDENT: Is there any potential for using that AI on our final paper to check--

R. SCOTT KEMP: Oh, yeah. So, yeah, so let me talk to you about your final-- I assume you will use AI tools. I can tell you not to use them, but I can't prove that you will not use them. So help yourself to AI tools, but don't forget, you have to defend-- you have to internalize that information, and the argument, and defend it. And AI is still not good enough not to make technical mistakes, factual mistakes on the scale of writing a paper. I have tried and tried and tried to get them to write final papers and they will not write good final papers.

So you need to-- using an AI to help you find information is great, but it's kind of up to you to make sure that information is complete, that it's relevant, that you believe it.

And we can talk a little bit about a good way to use AI-- basically, if you do not-- it might tell you things, and if you do not understand what it's telling you, you need to keep studying. You need to keep digging in until you understand it because it's too easy to make-- to just count on the answer and make mistakes. I'll give you an example.

I was recently writing a paper about melanocortin receptor 1, which is part of the melanocortin system in your neurotransmitters. This is one of my hobbies as I work on biotech. And I was like, oh, I need to know which peptides have binding affinity for this receptor. So I asked the AI because I didn't want to look up the molarity binding affinities in all the literature, and it gave me a table, and I was like, fantastic.

And then I was proceeding along, and later on I was like, something is not right here. And it turns out, yes, it gave me the binding affinities for mouse melanocortin receptors, not for human melanocortin receptors. Now, you can trip yourself up with your prompts, and you really need to know what data you're getting, check the sources. If there are no sources, don't trust it. So that's just an example of how AI can lead you astray. And you are on the hook for getting the right answer. OK. Yeah?

STUDENT: Does the AI critique for the sake of critiquing, or does it also point out what you do well? Because I can make an AI argue for or against the same point.

R. SCOTT KEMP: It writes two sections. The first one is like, oh, you did a good job on this, but you could have done a better job on that. And then it says, and here are all the mistakes you made. So, yeah. OK. Any opposition to this? People feel good about where they're settling down and where they're going to check the box on whether they're going to do homework or not? Sounds good.

All right, let's talk a little bit about the class lectures. I want this to be a discussion friendly-class. In the beginning it was like a seminar. Now it's too big to be a seminar. But if you feel that something isn't right and you want to speak up, definitely do it because it will enrich all of our experience.

There's no canon of knowledge in this class that you need to walk away with. This is not differential equations where if you don't get to the series solution at the end of the semester, you screw yourself on knowing how to solve complex differential equations, it's not like that. There's so much information about policy choices around nuclear energy that we cannot conceivably cover even 10% of it in this class.

This is just to give you a smattering of what's going on out there, in my perspective, on what is the most defensible position on different things. But if you feel like I have ignored something or you don't understand something and you want to push back, do it. I totally encourage this kind of debate because that's what we're all about. This class is not really debate, more dialectic, that we want to have this back and forth in pursuit of the truth, and that's the goal.

And everyone brings biases to these issues. I bring my own set of biases. I've been in been here for 14 years and have a sense of what the nuclear industry does, and I see it a certain way, and I'm going to present that. But you may wonder, why-- this is not how you've heard-- this is not what you've heard, and I completely welcome you to give your perspective and share it with the class.

OK. Let's see. All right. That's it for preview. Any last questions? In that case, in the remaining hour, I'm going to try to cover 110 years of history. And I don't-- people come to nuclear from all different backgrounds, and a lot of people here-- I know for a fact that many undergrads join the department because they like the people, and they don't really know a lot about nuclear.

Whereas the grad students, you've been around nuclear for a while and you probably know something about it, but not all grad students. Sometimes people have undergraduate degrees in chemistry or physics, and now they've decided to try nuclear. So they may not know the whole history of nuclear.

So we're going to go just go through the history. It's very basic, but it's just to give you a sense to set up an understanding of why things look the way they do, especially here in the United States. Most of this class is focused on the United States, and so it was just going to give you some of that history.

OK. So this strikes me as very dim, but I don't know if I can do anything about it. I'm sorry. I'll work on that later. So the discovery of nuclear energy is fascinating in the sense that its origins are actually the question, why do the stars shine? I don't know, has anyone-- do people know this? How many people knew that nuclear energy was discovered for a reason?

All right. So what happened is, early on, it was assumed that the sun was burning like a lump of coal in the sky. And Hermann von Helmholtz then showed that this probably couldn't be right.

Given the sun's luminosity, which is a measure of its total power output, if it-- and its apparent size, which they could measure, they said if it were just burning chemical reaction, then it would have burned out in a few thousand years. But they knew that that at that time, human history had already extended more than a few thousand years, so it couldn't be-- it couldn't be burning.

So Helmholtz proposed a new mechanism. He decided that perhaps gravitational contraction from the mass of the sun was actually driving the expulsion of energy. If you will, a conversion of gravitational potential energy into heat energy. This is called the Kelvin-Helmholtz mechanism. It's a real mechanism, and it is active in stars.

And he did a calculation. He said, oh, if we take into account this mechanism, the sun would burn for 20 million years. And that seemed like a suitable explanation for the sun. 20-- what did I say? 20 million? 20 million years. 20 million years.

So that was, for a moment, considered a good answer, but the problem was that at the time, geologists believed that Earth was essentially timeless, that it had existed forever. And that raised this weird question. Like, if the sun were, in fact, only at most 20 million years old, how did the Earth hang around and do things while the sun got formed? Why didn't it somehow disrupt the Earth at that time? So that was a problem.

But then Lord Kelvin, of the Kelvin thermometer, came around, and he measured the cooling rate of the Earth. He said, let us assume that the Earth starts as a ball of lava, or molten rock, and then it cools at a certain rate, how long would it have to cool in order to get the crust depth that we estimate exists today?

And he said, well, it turns out, it looks like it must have been cooling for somewhere between 20 to 100 million years. And since we know that the sun is 20 million years old, then this is more or less consistent and everyone was happy. So the Kelvin-Helmholtz mechanism was great.

But then, this other guy came along named Henri Becquerel. Becquerel is, of course, the unit of radioactive decay, and Becquerel said, oh, wait a second, there's all this radioactivity in the Earth, and when it decays, it's contributing heat. So yes, it is cooling according to Kelvin's calculation, but it's also being warmed by radioactive decay.

And then when you add that warming, it implies that the Earth can't possibly be just a few tens of millions of years old, it has to be billions of years old. And now we had a problem. How was it that the Earth was billions of years old, but the sun was only 20 million years old?

So there was a paradox. And it strongly suggested that this Kelvin-Helmholtz mechanism was not sufficient. The clue came from this plot, which is called the Hertzsprung-Russell diagram. Many of you may know this is as a main line sequence. It's a plot showing the star's luminosity on the y-axis, and on the x-axis, its surface temperature, and its blackbody radiative temperature.

And what stood out was that the stars were not scattered-- each one of these dots represents a star, and the stars weren't scattered uniformly. If the Kelvin-Helmholtz mechanism applied, we would expect that the luminosity of the star would scale directly with the mass. But that did not appear to be the-- in this case, there would be no order necessarily on this chart.

But there was this weird order on this chart, and that led to the conclusion that there must be some underlying mechanism that controls both luminosity and the temperature, but they didn't know what it was. But there's something that gave rise to this effect.

Then they started measuring the mass of stars. They did this by looking at binary stars that orbit each other, and they can calculate the masses, and they found out that this is, in fact, a plot of mass. So that indicated that, in fact, the luminosity did not scale linearly with mass, but actually, it scaled to the third or fourth power of mass.

And from that, they concluded that a homogeneous energy source, like the Kelvin-Helmholtz mechanism, was not a sufficient explanation. There had to be something where the energy production had great dependence on temperature so that as the mass went up, it would-- the energy production was skyrocket maybe at the center of the star. And indeed, the existence of these different regions suggested there might be different mechanisms.

It turns out, as labeled here, these are all different fusion mechanisms that come into play. But they didn't know what these were initially. They just recognized that there was some other process.

One year after the end of World War I, in 1920, the greatest probably astronomer of the 20th century, Arthur Eddington, wrote this. "The sun is drawing on some vast reservoir of energy by means unknown to us, this reservoir can scarcely be the other than the subatomic energy, which is known very recently--" the discovery isotopes was 1919, a year earlier, "that existed abundantly in all matter.

The suspicion has been generally entertained that the stars are the crucibles in which the lighter atoms, which abound in the nebulae, are compounded into more complex elements." This is the R process. This is how we get heavy isotopes. You just-- it's just a suspicion. "We sometimes dream that man will one day learn how to release his energy for its use."

He was completely right. This is indeed what is going on in the stars. But the very prescient Eddington is even more prescient than we might realize because he concluded, "This latent power could be controlled for the well-being of the human race-- or for its suicide."

See, he recognized, even in 1920, that having the ability to manipulate something with such energy density as exists in nuclear energy meant that you could do wonderful things, like make electricity and power the world, and you could do terrible things, like make nuclear weapons. So long before-- this is why nuclear weapons show up in sci-fi literature well before they were ever invented, because of this understanding and realization.

And, in fact, this is more true than you may realize. Of course, Eddington is not talking about fission, he's talking about energy release from fusion, but in most modern nuclear weapons, the majority of energy-- the vast majority of energy comes about because of fusion processes. So, yeah, this is, in fact, the exact same stuff that is driving the bombs.

All right. So fast forward 13 years, we are in 1933, the same year the Nazi Party took over Germany. It began to blame the Jews for the economic distress of the country imposed on it by the agreements that ended World War I.

Einstein, as a Jew, flees to the United States. Many in we're in Europe are, of course, worried about this German nationalism, German rearmament that's happening. They had just finished World War I, no one wanted to see another World War, and people were trying to get out of there fast.

That September, this guy, this is Leo Szilard. He's a Hungarian physicist, and he's really the father of nuclear engineering. He invented the nuclear reactor, he invented the breeder reactor, and he invented the closed nuclear fuel cycle. So he's a very important figure in our field, although we don't talk about him very much, but he was at the beginning of it all.

And here in September 1933, he had just imagined the idea of a nuclear chain reaction. He said-- this is from his memoirs, "I was waiting for the light to change, and as the light changed to green and I crossed the street, it suddenly occurred to me that if we could find an element which is split by neutrons and which would emit two neutrons when it absorbed one neutron--" like uranium, "such an element, if assembled in a sufficiently large mass, could sustain a nuclear chain reaction. I didn't see at the moment just how one would go about finding such an element."

Now, since the early experiments from Eddington and others, the idea of binding energy had come about, people had measured the binding energy and found the curve of binding energy so that if you break apart large isotopes, you get energy out, if you fuse light isotopes, you get energy out. And people were manipulating these isotopes by shooting various things at them and looking at what happens.

But to be clear, nobody knew of anything called fission. It was mostly end-to-end reactions, p, n reactions, very simple nucleon-nucleon kinds of things, and some radioactive decay. So he had this idea of some chain reaction. In fact, there are various proposals using-- I forget, like beryllium and weird things on how to create the chain reaction in the early days. Of course, none of them would work.

But because a chain reaction would lead to the uncontrolled release of energy, he knew immediately that that was going to be a problem. And so he filed a secret patent with the British Navy on the concept of the chain reaction in an attempt to control the technology.

OK, so the next year, an Italian physicist named Enrico Fermi, who is my advisor's advisor, was playing around with uranium, and he noticed that when he shot neutrons at the uranium, all kinds of stuff came out. And he wasn't sure what was going on.

This wasn't recognized initially as splitting of the nucleus. That the nucleus could be split was originally proposed by this German woman named Ida Noddack, but she is completely lost to history and has never received any credit for the fact that she had originally proposed this idea of fission. Four years later, in December 1938--

STUDENT: Can you say her name one more time?

R. SCOTT KEMP: Ida Noddack.

STUDENT: Thank you.

R. SCOTT KEMP: Yep. Four years later, in 1938, another German, Otto Hahn, and another woman, Austrian Lise Meitner, Fritz Saltzman, shown here, argued that-- and experimentally demonstrated that, in fact, the nucleus was fission. They are the ones who popularly received the credit, but it was originally Ida's idea.

This fissioning of uranium was not yet linked to any chain reaction. It was simply thought that when you shoot neutrons in uranium, it breaks apart. The idea that it could sustain a nuclear chain reaction would require it to generate more than one neutrons, that had not yet been observed.

But then, four months later, in March of 1939, Frédéric Joliot, French physicist, showed that uranium fission, indeed, neutrons came out. How many? Not exactly clear, but neutrons came out. And then he eventually showed that it was more than one.

While this is all going on in the world, the discovery of fission, there's also a lot of work going on in fusion. So in 1934, this is the same year that Fermi discovered that uranium does weird things, there was all this work on plasma confinement. A lot of people were talking about the linear pinch and Z-pinch. And there were some early ideas, mostly developed by Bennett in the United Kingdom. This stuff was not really being done early on in the US.

But the basic idea here is that you pass a current through this ionized gas, it creates a magnetic field, right-hand rule, and it compresses the compresses the gas on itself. And if you could get that to happen fast enough, potentially you can make fusion. And we still have people who are working on Z-pinch drivers for fusion.

You may be aware of the Z Machine, which is a giant bank of capacitors that basically does this not by pinching the gas, but in a little metal capsule, and it compresses the capsule and attempts-- and does actually successfully work and create fusion, you just probably can't make it economic. But we use this machine to create fusion neutrons for diagnosing nuclear weapons and doing all kinds of stuff here in the United States.

So by the time fission was confirmed in 1938, these studies were just starting to show up in the United States. So Joliot was busy trying to count the number of neutrons coming out of uranium. And meanwhile, the Nazis are violating the Treaty of Versailles that ended World War I. The Japanese imperialist government had begun attacking China. Fascist Italy withdrew from the League of Nations. Germany begins to annex Austria. The whole world is falling apart.

And the last straw was in that September, the Germans invaded Poland, which the rest of the world can no longer close its eyes to and say, oh, of course, it was part of the traditional German fatherland. Yeah, it was a clear invasion, and that led to the Allied powers declaring war on Germany.

So understandably, Mr Leo Szilard, who, from the beginning, was worried about the chain reaction-- and you heard about Joliot's experiments counting neutrons, he went to Joliot and said, if it is more than one, please do not publish your result because it will show that uranium can be used for a chain reaction, and everyone knows, going back to Eddington, that that means we can make a bomb out of nuclear energy.

So here is the first real moral dilemma of the nuclear age. What would you have done? Yeah?

STUDENT: I think published the research because someone would find out eventually and I still kind of believe that the information itself is neutral and it's how we use it.

R. SCOTT KEMP: Yeah, that has always been the argument that has always been made. There's another famous person, Gernot Zippe, who invented the uranium enrichment gas centrifuge, which, of course, Iran has used to try to build a nuclear weapons program, among other countries. And he is always on-- he is quoted as saying, "With a kitchen knife, you can make a sandwich or kill a person," the technology is neutral. It's a certain perspective.

But Szilard had a different view. He's like, maybe the technology is neutral, but we can also wait. This is not the time, we are going to war with Germany, let's just wait. Joliot published the results. He showed that, indeed, more than one neutron could be released-- was released, and that meant any nuclear physicists worth their salt here at the dawn of World War II knew that a nuclear weapon was possible.

OK, so what happened? So Szilard panicked. Joliot published in March of 1939, and Szilard decided to write a letter to the President of the United States saying, this is an emergency, we need to do something about this. But nobody knew who Leo Szilard was. And so Leo Szilard took his letter out to Einstein's house on Long Island and said, would you please sign this letter and pretend it's from you? And so that's what Einstein did.

And as a result of receiving this letter signed by Albert Einstein, the President set up the Uranium Committee. The Uranium Committee's job was just to investigate uranium fission. various sites were set up around the United States. The reactor in Chicago, a place at University of Chicago, a place at University of Columbia was set up to look at uranium extraction from the ground.

When I was a grad student at Princeton, their version of EHS, Environmental Health and Safety, called me up one day and said, there is a radioactive filing cabinet in the basement of the engineering building, can you please come and have a look and tell us what this is? And it turned out, it was the Uranium Committee original lab notebooks from doing uranium separation from ores, and there was all this liquid spilled on the pages, and thus, very mildly radioactive. So yeah, that was a fun little thing to do as a grad student.

This was basically not-- this was not the Manhattan Project. It was a little more than just organized research. It was-- the President wasn't panicking in the way that Szilard was panicking. And Szilard didn't want a bomb to be made, he just wanted to investigate to see what the situation was because he didn't want the Germans to get there first because we did nothing but sit on our hands. So that's all it was. It was just a research project.

Then two English physicists, Otto Frisch and Rudolf Peierls, wrote a memo to their British government saying, hey, we could build a bomb. And here's their memo. "The attached detailed report concerns the possibility of constructing a," quote, "'super-bomb' which utilizes the energy stored in atomic nuclei as a source of energy.

The energy liberated in the explosion of such a super-bomb is about the same as that produced by the explosions of 1,000 tons of dynamite." a factor of 15 off for first generation. Not too bad, a little low. "The energy is liberated in a small volume, in which it will, for an instant, produce a temperature comparable to that of the interior of the sun. The blast from such an explosion would destroy life in a wide area. The size of this area is difficult to estimate, but it will probably cover the center of a big city."

This is very remarkable because at the time they wrote this memo, no chain reaction had yet been demonstrated. There was no nuclear cross-section data for these isotopes. They just did this from first principles. This is the magic of being a really good physicist. And they basically got it right.

The British started a program, which was codenamed the Tube Alloys Program. As soon as the British started this weapons program, the United States says, well, we're not going to let the Brits do this by themselves. And so the United States, the British, and the Canadians, often forgotten, got together and started the Manhattan Project, and that, of course, led to the production of the bomb.

Of course, the rest of the Manhattan Project history is nuclear weapons history. I won't get into that today, but the important reason to bring this up is to get you to realize that here now at the birth of the discovery of nuclear energy, this was now a wartime weapons program, and it was instantly surrounded by enormous amounts of secrecy.

So for fission, the connections are obvious. The first reactor built at Stagg Field at University of Chicago, and the production reactor's later built during the Manhattan Project at Hanford in Washington State, were all done in secret. How you build reactors were secret. Nuclear data was secret. Everything was secret.

It also actually applied also to fusion. Initially, all the fusion concepts-- most of the fusion concepts were secret if they were developed in the United States. We were late to the game on fusion, so things like the Z-pinch which came from the UK, were not secret, but the stellarator, for example, it was invented by Lyman Spitzer, secret.

And Princeton-- the Princeton Plasma Physics Lab, if you are in the fusion world, about PPL, PPPL, and that was all set up in response to the Manhattan Project.

Secrecy means big bureaucratic institutions. Secrecy means a security apparatus. And it means two classes of people, those who get to know and those who don't get to know. And when you have that kind of arrangement, you have the people who are in the know having a vested interest in protecting their community and their groups, and saying all kinds of stuff to people who don't know to make sure that their activities get protected and keep this club exclusive and so on and so forth.

And so this set the stage for strong government involvement and all nuclear research, including research on things like just peaceful nuclear power. The government owned everything, it's deciding what was secret and what was not secret. There was a report called the Smyth Report, which was the initial decision about what, from the Manhattan Project-- what information we would release and what information would be kept secret.

If you want, one of the first mimeograph copies of the Smyth Report stapled is sitting in my research group, well before it was ever printed by any government printed office-- printing office, so you want to come see it. And that meant that there was also going to be just a lot of money going into this because this was a national security priority of the US government.

People today like to complain that the renewable people are getting subsidies from the government and so on. The nuclear people got subsidies. In the beginning, nuclear had so much government support for the first 11 years of its existence.

In the end, Congress created the Atomic Energy Commission, better known as the AEC, that would control all nuclear research, public and private, whether for military or for peaceful purposes. And never before or since has a government been so heavily involved-- or has imposed itself so directly in the emergence of a new industry. And that has completely shaped how things have turned out.

So as this was happening, there was an important change happening in the post-war environment. No longer was this a wartime project, but it was still very political and strategic. After World War II, the rest was concerned about the Soviet Union.

And the Soviets had been, of course, our allies in World War II, and many, many, many Soviets died fighting the Germans on the behalf of the Western countries, but then popular communism in Russia, and this was leading to criticism of Western capitalist approaches. And as a result, the world appeared to be dividing along ideological lines.

Eastern European countries increasingly turned towards Russia, joining the Soviet Union. The West was opposing this because they saw this divide that happened once again, just like the divide that led to World War II, but no one had an appetite for another hot war, a third World War. And so this became what is known as the Cold War. And it was going to be a war fought on the territory of ideology, and nuclear power turned out to be one of the first Battlefronts.

So the generals of this nuclear power battle were the commissioners of the Atomic Energy Commission. The head of the commission was David Lilienthal. Lilienthal had been an American attorney who ran the Tennessee Valley Authority, TVA. TVA was, at the time, the biggest electric utility in the United States. It's still one of the biggest utilities.

It was formed after the attempt to build a bunch of dams to control flooding along the Mississippi River, and as a result, you have a bunch of dams, you have a bunch of electricity, they became a giant energy producer.

And when you built the enrichment facilities to make enriched uranium to build the first nuclear weapon during the Manhattan Project, you needed a ton of electricity, so they went to TVA, and TVA was very intimately engaged in the Manhattan Project, basically powering all these facilities. And so afterwards, the head of the TVA was selected to be a commissioner of the Atomic Energy Commission.

Another guy, Strauss, Lewis Strauss, is the evil villain in the recent Oppenheimer movie. If you saw the guy trying to take on Oppenheimer, that was Strauss. He was a philanthropist, very rich from the beginning, very politically connected, and he believed that nuclear energy-- basically viewed nuclear energy in a way like people view AI today, this is going to be the way to get rich.

So he wanted to do this. Gordon Dean, actually not on this photo, was an investment banker. I mean, all these guys were basically business guys. And they worked side by side with nuclear physicists, but none of them were nuclear physicists themselves. None of them really understood anything about science or technology, but they understood business. And they saw a bright future for nuclear energy, a big, beautiful, bright business future that was going to make them all very, very rich.

So they didn't know how it was going to be done. Strauss was actually a very big proponent of fusion. He went on to famously say that thermonuclear fusion was going to be so revolutionary that it would power the world and it would be, quote, "too cheap to meter." If you've heard that quote before, that came from Strauss.

But basically, they all wanted to get in on the ground floor. They all wanted to be Nvidia, making the hardware that would power this nuclear revolution that would power the world. And who better to provide this-- the chips, if you will, for the atomic revolution but US companies? Fission companies that they have ownership stakes in.

And so to do this, the AEC adopted this plan of open-ended research, as any good business person would do. We don't know how to do this. We get all the smart people in the room together and let them just come up with ideas and see which ones stick.

They didn't want to prematurely settle on any particular technology and then make a mistake. They knew from the beginning that they needed a commercially viable product, and their goal was to find a way to make nuclear energy cheaper than coal. That was their official goal.

But all of this had to be done in classified channels through the government, which actually suits their interests. That gives them tremendous control and means there are no competitors that they have to worry about, no startups. It's going to be their people, they get contracts, and that was great.

Well, in the world of fusion, the AEC said, OK, let's support the toroidal pinch, the mirror machine, and the Lyman Spitzer stellarator idea. All these programs were built up in the United States in secret. In the land of fission, the AEC searched around for reactor designs. They did the RFP, Request for Proposals, on how to-- we had built reactors at Hanford to make plutonium, but those were not power reactors. They were not optimized for power, so we need power reactor ideas.

So we put out an RFP-- you know how many ideas for different reactor designs they got back? 80. 8-0. I mean, it blows-- I cannot possibly list 40 reactor concepts, nevermind 80. I mean, this was really the true-- truly the beginning.

Of these 80, and they downselected to five reactors to pursue in parallel. There was the homogeneous reactor, which is a uranium and water sludge in a ball because the idea was it would be very simple to build. Maybe it will actually be cost-competitive with coal.

Unfortunately, things like precipitates happen, and then that affects the criticality, and that is not a good concept. But that was one of the early ideas they pursued.

Sodium graphite reactor, they're experiments that went on to become EBR-I and II. And EBR-I and II is here. Sodium reactor-- I guess this probably was a fast reactor, but maybe not a breeder reactor. A lot of ideas. Sodium graphite reactor because it would use less uranium, and, of course, a water-based reactor because it seemed to be technologically straightforward.

All this was happening with giant government-funded programs. This was the golden era of nuclear engineering. As long as you were part of one of the ordained companies, you got lots of money and could do lots of crazy things.

1953. President Eisenhower-- General Eisenhower, one of the only people who could probably do this, said, we need to cut-- we spent so much on the war, we need to cut government spending. And across the board, including in militarily significant domains, there were major budget cuts, and the AEC was forced to terminate all of these programs. But then something saved fission, but not fusion-- the US Navy.

So it had-- the US Navy had its own interest in nuclear power. It didn't care about making electricity, but it wanted nuclear reactors to power ships, and in particular, submarines. The submarines of the US Navy at the time were diesel submarines. They had to snorkel with something to suck in fresh air, they ran diesel generators that were charged batteries, and then they had batteries they could submerge.

At that time, American submarines kind of sucked. Soviet submarines were much better than American submarines. They had better batteries, they were quieter, they could stay submerged longer, and that drove the US Navy nuts.

And they were particularly concerned about a revisit of what happened during World War II, when the Germans, who made the famous U-boat, which were basically death traps, but they were churning these U-boats out at the rate of 25 per month, about one submarine per day.

And the Navy was saying, if the Soviets, who we're now in a Cold War with, attain German production levels, and their boats are already better than our boats, they can basically have free reign and do whatever they want in the oceans, and this is a crisis, and there's going to be a second Pearl Harbor, and we need to do something about this.

So their idea was to leapfrog ahead by using nuclear power to build a better submarine that could stay submerged indefinitely, did not need to snorkel, and would be faster and better in all sorts of ways than the Soviet boats. And they went around to Congress trying to drum up money for this and kept saying, second Pearl Harbor, and that was a very effective line of argumentation.

So what was the Navy's objectives here? Well, they wanted a-- they want just a reactor that was going to be small enough to fit in the hull of a submarine, more than anything, and that was comfortable and familiar for naval engineers. So naval engineers were comfortable designing things with water.

The chemistry of water and chemistry of corrosion is something that-- water-based corrosion was something they understood. Water makes a great working fluid because a lot of energy goes into the phase change. And it is a great moderator because there's a lot of hydrogen, which means that you could make the reactor small, the core small.

So for all of these reasons, the pressurized water reactor was selected as the optimal reactor for powering boats. It was not selected for its economic competitiveness, and it was not selected because it was safe. On a submarine, the principal concern is that when the torpedo is coming at you, your boat can go fast and get out of the way of the submarine. That's how you save the people on board.

If the nuclear reactor has a meltdown once every 100 years or once every 10,000 years is irrelevant. You need to go fast, that's what's relevant. And that's what the nuclear reactor enabled them to do. So they didn't care about things like overall safety of the reactor.

And so now we have two parallel efforts. We have the Navy pursuing the pressurized water reactor, very singlemindedly because they need to defeat the Soviets, and we have these business guys over at the AEC who are doing this open-ended research, exploration of the entire phase space and just had their budget cut.

And so you can guess, when the budget cut came, how this shook out. The Navy wanted, of course, to keep their program going. They wanted to escape the budget cuts. And they had built a whole lot of political support in Congress by saying, second Pearl Harbor, second Pearl Harbor.

And in order to further cement that they would have ongoing funding, they went to Congress and said, look, we know the AEC is doing this reactor thing. We're also doing the reactor thing. And guess what? You can put Navy reactors on land. They look like little submarines.

And you can make electricity with them. So there's no need to send money to the AEC. Just give us all the money, and we'll do all the research, and you'll kill two birds with one stone, and you'll save lots of budgetary money, and everything will be happy. And, of course, you don't really have any option because second Pearl Harbor. And it worked.

And so the AEC was, of course, very unhappy. Not only did the AEC want its own money, like every institution, but their experts had already looked at the pressurized water reactor and dismissed it. It was not one of the initial five choices. And the reason they dismissed it is because they felt it was too hardware-intensive, it was not going-- because you had to deal with high-pressure water, you had to deal with steam heat exchangers, you have to do with a whole bunch of stuff.

You have to deal with water flow and cavitation and all these things that made the engineering hard. And they just thought it was not going to be economical. There was no way that, in their view, that this reactor was going to compete with coal, which their original objective.

And it's worth noting that the AEC was not the only group to have this perspective. So nuclear power is taking off all over the world, primarily in France and in the Western countries. It's happening in the Soviet Union, too, but France and UK were the first countries in Europe to really stand up a big nuclear research program. And they had also decided the pressurized water reactor was not going to be competitive. And they chose gas graphite reactors. That's what they thought was the way to go.

Unfortunately, the AEC failed, and back here in the United States, Shippingport was indeed built. It was, in fact, on budget and on time, probably the last on-budget, on-time reactor built in the United States.

I did a calculation recently to figure out what the electricity cost was from this reactor, and it's actually about the same as the current modal reactors that were just completed a couple of years ago, when you inflation-adjust it and everything else. Now this had none of the safety that a modal has, but it's amazing because the cost is basically unchanged in all this time.

OK, so the competition with the Soviets was heating up. We had the space race. We had the arms race. And now there was a kilowatt race to see who would put nuclear power on the grid first.

Congress decided that this was another battleground in which America needed to demonstrate the superiority of the capitalist system, and particularly, they wanted American-made nuclear power to be the nuclear power that was going to power the world. And that would bring all freedom-loving people together and make everyone an ally of the United States. It was very strategic and we had to do this.

So strangely, this belief had a rather positive effect on Fusion, but it turned out to be a really strangely negative effect on fission. So in the fusion world, there are all these conferences that happened, and ideas were declassified, and the tokamak was shown to the world, and things moved forward. It was all done in vein of just research, not making competitive nuclear power. But in the competitive nuclear power space, things went-- in fission, things went a little differently.

So in 1954, to cement this new perspective, Congress passed a revised version of the Atomic Energy Act, and this law was supposed to fix the stoppage that was caused a year earlier by Eisenhower's budget cuts. And what they said was, OK, we're going to support nuclear power, but private industry is going to build these reactors.

So instead of this huge amount of money coming from the government, the government is going to declassify all these concepts and let private companies build power, and that's how you do it in a capitalist system, not a state-sponsored system like the Soviet Union.

So the AEC licensed their designs. They went around and they said, well since we have a bunch of private companies, we can have more designs. And they said, OK, they licensed 10 concepts to private industry, and the private industry was supposed to fund this R&D themselves.

Well, the race for the Soviet Union was on. And just to illustrate how people looked at this, this is a quote from one of the senators. "If we are outdistanced by Russia in this race, it would be catastrophic. If we are outdistanced either by the United Kingdom or France, there would be tremendous economic tragedy to our commerce and international commerce of this great nation of ours."

People really thought that this-- we had to win this race, and that this private industry method was going to be the way to do it. There is the problem. We license these 10 reactor concepts to 10 different companies, and the companies sat on their hands. They didn't do very much. Why?

A, nobody knew which technology was going to work, and this company got this design and they're like, oh, yeah, no, we didn't invent this. And on top of it, there were nine other competitors out there and there were zero customers. So why are we going to mortgage the bank of our company to satisfy the AEC's pet project to build nuclear power? This is not our business obligation to do this.

So the AEC fixed this problem. They went to Euratom. Does anyone know what Euratom is? All right. So Euratom was one of the first three European communities created after World War II. These communities were ways to prevent European nations from going to war with each other again.

The three of them were the European-- the European Economic Community. That eventually gave rise to the euro currency. The second one was the European coal and steel community, which, of course, coal and steel was the principal sources of war-making machinery, and everyone exchanged, and had equal access. This would prevent any of asymmetric uprising of military power.

And the third one was this new forward-looking technology, nuclear power, and there was a cooperative arrangement to have all the European countries work together on making peaceful nuclear energy, and that way, there wouldn't be any one country who got ahead and could make a bomb and so on.

So that was the idea. The nuclear part was called Euratom. And negotiations for Euratom began in 1955, included in 1958, but here at the very beginning of the negotiations, the EEC is trying to solve this problem with companies sitting on their hands, and so they said, great, you guys want to do this whole nuclear thing in Europe, and you have a lot of countries, why don't you buy a gigawatt of nuclear power from US companies?

Now today, a gigawatt sounds not very much power, one reactor. But back then, it was a lot of power. It was about 10 reactors because reactors were a lot smaller at that time. People forget, we started with small modular reactors. So that was one European customer for each American company. Problem solved. That created an instant market for the Americans who were not willing to start. Now they had a guaranteed customer, they would invest money, that was the idea.

Well, why did Euratom agree to do this? Why didn't they just say, no, no thanks, we'll develop the technology ourselves. Doesn't seem very strategic.

STUDENT: Weren't they just destroyed post-war? And had fewer resources?

R. SCOTT KEMP: They did have fewer resources. That probably factors in at some levels. Yeah?

STUDENT: They were considered to be more safe under the US umbrella.

R. SCOTT KEMP: Yeah, I think the US umbrella is emerging at this time. It is certainly-- everyone is deferential to the United States because it played such an important role in World War II. But it's still early days. And I think countries like France and the UK really still saw themselves as wanting to develop their own technology. Italy. Also Germany-- also with Germany. Yep?

STUDENT: Would it be because of one of the countries developed it first, it would create a power imbalance?

R. SCOTT KEMP: No, that was the idea. It was like-- the Euratom thing was like a share. All right, I'll tell you-- oh, there was more guesses. OK, two more guesses and then I'll tell you the answer.

STUDENT: Was it because they wanted the transfer of knowledge from the Manhattan Project?

R. SCOTT KEMP: That's an interesting question. I don't know whether that was active or not. One more.

STUDENT: They thought it was unsafe? No.

R. SCOTT KEMP: No. No one-- the Americans paid them to do it. The Americans said, look, buy 10 reactors and we'll pay for 50% of the reactor. All right. But wait, the 1954 Atomic Energy Act prohibited the American government from spending money on private industry. Ah, this wasn't spending money on private industry, this was foreign aid.

So they basically laundered their money through the Europeans to fund American corporations. This is the kind of business backroom deals that happened in order to make this work out. So in fact, it was still government-funded, it was just being laundered through the Europeans.

All right. So that was the idea. They were supposed to kickstart the American industry, and things didn't work out. What happened? The Soviets beat the United States as the first nation to put a nuclear reactor on the grid. This is Abinsk, if you've never heard of the reactor. And connected to the grid in June of 1954.

The British then beat the Americans to put the first Western reactor on the grid. This was Calder Hall, a gas graphite reactor shown here. Queen Elizabeth flipping the switch to connect reactor to the grid, very politely. And 1956, Shippingport, our submarine reactor, was finished in December 1957. So we just could not catch up. The Europeans were beating us.

OK, so what happened? The AEC is like, this is not working out. And so instead of selling Europeans one of every design from the 10 different companies, they said, we're going to lose the market to this British reactor, and what we're going to do is instead just sell 10 copies of whatever American reactor gets finished first, and that reactor was the PWR. And so that's how the PWR became the reactor du jour.

The other nine designs basically fell by the wayside once the AEC announced this project that they were going to sell 10 copies of the PWR, Pressurized Water Reactor. Corporations were no longer interested in spending their money to develop other, potentially cheaper, potentially safer reactor concepts. It was not-- there's no more customer for them.

And so we chose a technology-- a technology winner without ever doing a technology evaluation. It was chosen for political reasons, for reasons of having American business win, but one can ask, what would have happened if we had actually done that systematic evaluation of all the different possible type of nuclear power?

Would the history be different? Would it have cost less? Would there have been fewer accidents or safety issues to deal with? Would the safety cost burden be lower because it didn't have to deal with pressurized water? These are all kind of questions that we can't answer.

One of the challenges, of course, is that once you choose a technology, it becomes the only obvious way to go forward because there's so much sunk cost investment, R&D in that technology, so much about it, it's the obvious path forward, and it's really hard to escape that and look at other ways of doing things. The internal combustion engine is a great example of that. It's just very, very sticky. It gets institutionalized because that's how people are trained.

They learn on that design. Then in the case of the internal combustion engines, all these gas stations showed up to pump gasoline, which could have been something else, and so on and so forth. And it just becomes entrenched. And that is what happened to the PWR. So, of course, the history of the PWR is a strange history, and we will pick up on this in the next class.