[AUDIO LOGO]

DAVID KAISER: OK. Let me start. I'll share a screen, and we can start today's material. So on Monday's class, we talked a bit about some of the kinds of work that was going on, largely within Germany or at least other parts of Europe, but a lot of it right within Germany itself around topics like the discovery of nuclear fission and early efforts to put nuclear fission to more practical use, including both for early ideas about nuclear weapons as well as for power generation nuclear reactors

And we saw that was deeply, deeply bound up or caught up in this head-spinning swirl of the onrush toward the Second World War, the rise of the Nazis, the soon overt fighting across Europe and, of course, much beyond that before long. So Monday's class was largely about developments within Europe.

And today, we'll talk about a range of developments, mostly in the United States. And so we have, as usual, three main parts for the class. Here at the bottom is my note reminding us, again, as I just mentioned, about the film *The Day After Trinity,* and I wanted to add that note because the course material today, the lecture for today, is mostly going to be looking at conceptual ideas, physics and engineering ideas, as well as new institutions or institutional arrangements in which many physicists began to find themselves.

And we won't be talking in today's class session about broader questions, ethical, moral, contextual about the actual use of these new weapons. And that's partly I want to make sure that we do have time to talk about that, at least to start those discussions with our optional discussion section on Monday. So today we'll be not exactly a technical history of the wartime projects. But we'll get into a bit more of, what did physicists, mostly in the United States, find themselves being drawn into or being wrapped up with during the late '30s and throughout much of the 1940s?

So we'll start, actually, by talking a bit about radar, which often gets kind of overlooked these days. The drama of the nuclear weapons tends to obscure many, many other full-tilt defense projects or weapons projects that physicists and engineers were really immersed in during the war. And so we'll talk about radar for a good chunk of today. And then we'll shift and talk about some aspects of the Manhattan Project and the film will cover other kinds of aspects in addition.

So let's talk first about radar. So radar was around since before the Second World War. The first working units had been developed actually in many countries independently. Simultaneous discovery is a phrase that historians will often use. There were groups working independent of each other in different countries in Europe and the UK, some in the United States, in Japan, in Soviet Union and other places, it's been found, that all came across similar ideas-- came upon similar ideas in the mid 1930.

The idea for radar is to emit electromagnetic waves, Maxwell waves, classical radiation, let those waves reflect off of some target, some object, and then collect the echo, collect the rebound, the reflected waves that come back to your device. And then you can do things like use the fact that these are Maxwell waves. They're electromagnetic waves. They should be traveling at a constant speed of light.

And if you have very good electronics, good timing, then you should be able to measure the difference between when you send out your own pulse when you generated your waves and when you receive the echo. So that gives you the time. And if the constant speed at which those waves are traveling, you can then determine the distance toward that object or your target.

That was the original idea. There were working units, as I say, in many parts of the world already by the early and mid 1930s. More sophisticated units that were developed actually during the Second World War, so by the early 1940s, built in a very clever addition, which was to measure not just the time of arrival of that echo but also measure the frequency shift.

They had very quick Doppler analyzers to measure the shift in the frequency of the return signal compared to the signal that the unit had sent out. So then you could actually measure the speed-- at least speed along the line of sight-- of the target object as well. So now these devices could measure both distance and speed of the targets, much of that before the start of the war.

So both British and us based researchers had developed these long wavelength radar systems. And by long, that meant the wavelength was measured in meters, sometimes tens or even hundreds of meters, more radio waves. And those were what had been operational before the start of the war. And then once the war actually broke out, once UK declared war against Germany and US began to mobilize even before it declared war officially, that was really one of the earliest experiences that many, many physicists in these parts of the world had with a direct involvement with military matters.

So it was the radar project that was for many, many physicists and other engineers, physical-science-based engineers, this was, for many of them, their first experience working closely on direct military projects. So one of the first challenges, a real, genuine, hard research challenge was to design new kinds of radars that used much shorter wavelength waves, so make the outgoing signal not meters or tens of meters but more like centimeters, or at most say, tens of centimeters.

They want to shrink down the wavelength of the outgoing signal. And that was because the nature of the challenge had shifted quite dramatically. Remember, with shorter wavelengths, you can resolve. You can make sharper images of smaller-scale things. So if you only have a very long wavelength wave, you'll never be able to make out short-scale, short-distance phenomena.

Why would they need suddenly to worry about centimeter-scale phenomena instead of meters? After all, airplanes are many meters long or large boats on the water. The problem was, beginning with right around the outbreak of the war itself, the famous or infamous German submarines, the U-boats, had become an enormous threat, a very deadly threat to both US and UK shipping interests, both for commercial shipping but also for Naval ships as well.

Now the boats were ordinarily underwater. They were basically impervious to this kind of radar. But if a part of the boat would reach the surface, often as little as just a periscope, just a little sighting device to allow the members on the German subs to see their targets, if that breached the water, that would be a couple of centimeters scale target for these radars. So in order to try to have any hope against this now very deadly force of the German U-boats, the radar challenge became to find centimeter scale radar systems, not just meters or tens of meters.

OK, so by 1940, just a few months into the real heart of the U-boat campaign, physicists and engineers within the UK had really made a huge advance. They had developed what became called the cavity magnetron. And here's one shown in the image here.

You don't get a clear sense of scale. This is just a couple centimeters across. You can hold it in your hand. This is a handheld scale device that could emit very high power, high intensity electromagnetic waves of this shorter wavelength, of roughly one or early ones or were about three centimeters wavelength instead of meters. So you could create very powerful outgoing beams of short wavelength electromagnetic waves.

By that time, however, the UK was under both bombardment from the air, the German Luftwaffe. The German Air Force was now doing very, very successful bombing runs, penetrating London airspace routinely and with devastating effects. So the blitz, the bombing in London and other parts of Britain was nearly constant.

And so it seemed impossible to scale up this kind of bench-top level research into really full-scale research, development, and production. So they knew how to make one or two of these devices. They didn't know how to make factories worth, humming around the clock to make hundreds and thousands of these devices because that kind of industrial capacity was under constant threat from. Bombardment

So in the autumn of 1940-- and remember, that's more than one whole year before the US even officially entered the war. So long before the surprise attack on Pearl Harbor, which finally was the reason why the United States officially entered the Second World War, long before that, a British delegation came over, quite a dangerous journey. They came over by boat, despite the German submarines.

It was a delegation led by Sir Henry Tizard. It became known as the Tizard delegation. They came to the United States. And they set up a meeting in Washington DC to try to get US-based colleagues to partner and ultimately take over the lead on these next steps for radar development. They wanted to cooperate, but especially, have a safer home base or a headquarters within which this work could then be expanded.

They came over with lots of blueprints, lots of paperwork, and also, literally one, one cavity magnetron. They were so rare, and they were in such high demand back in Britain, they could spare only one to hand over to their US colleagues. And the idea was between the paperwork, the specs, and the blueprints and the technical reports and literally the one working device, the hope was that these groups in the US could reverse engineer this thing, make many more of them, and improve the design.

So at this meeting, which was held in a fancy hotel in Washington DC, it was a small group of US colleagues who attended who met with Tizard and his British team. But it included a heavy dose of MIT folks. So, in particular, it included Vannevar Bush, who had only just recently left MIT by that point to work full time in science policy at science advising in Washington DC. But until that time, he'd been the Dean of Engineering at MIT, came from electrical engineering himself.

Likewise, attending this meeting was Karl Compton, the physicist, who at this point, was president of MIT. There was a dominant MIT presence in this top-secret meeting in this Washington DC hotel. And at one point, Compton actually literally stepped out of this meeting to place a phone call to one of his assistants who was back here on campus at MIT to see if MIT could spare space to be the place to build up the headquarters for this new Allied effort in radar.

The biggest stumbling block was that there was a big faculty parking lot in the middle of campus. And you might know that then as now, faculty parking is super precious and rare. And so the concern that the president of MIT had was whether the campus could basically take over that parking lot to build this temporary laboratory to do work on radar. And the grudging response was yes. That's where MIT'S famous building 20 then wound up being built.

None of you probably has seen building 20. Was torn down in the mid '90s. It was a temporary building literally built out of plywood. It was not meant to outlast the duration of the war. It was in constant use, in fact, for 55 years, much beloved on campus.

It was only torn down to make space for what's now this Stata Center. And here's a picture, you can see the 1940s vehicles. It was literally a large-scale but temporary facility right in the middle of campus, famous building 20. That became the original headquarters then for the MIT-based Allied efforts in radar. It became known as the radiation laboratory or just the Rad Lab.

OK, so this project became one of the earliest and largest projects sponsored by this new institution within the United States called the National Defense Research Committee or the NDRC. This was also a kind of brainchild of MIT'S Vannevar Bush. So Bush, because of his time in DC, he knew a US President, Franklin Roosevelt. He convinced Roosevelt and Roosevelt's immediate circle of advisors that the US, although it was still not officially at war, should begin mobilizing or getting ready. It looked like war could spill out and involve the US at any time.

So Bush's idea was to make a meeting place, an institution that could help connect researchers in science and engineering, some at universities, some at industrial laboratories in the private sector, connect them with US military officials. The idea was that the military could come to Bush's organization, the NDRC, say, we really need a better this or a better that. Could you please get people to work on it? So the NDRC would be the kind of meeting ground to help arrange these contacts.

So a little while later, roughly one year later, still well before the US even entered the war, Vannevar Bush convinced Roosevelt that wasn't enough. That just being able to arrange for research contracts was actually insufficient, and that in fact, there should be an even an expanded institutional base that became known as the OSRD, the Office of Scientific Research and Development and that Bush would lead that.

So not only would the OSRD let out contracts like the older model, but it would actually have a much more active and ongoing role in production. It wouldn't just say, here's your contract. Tell us when you're done. It would have a steady oversight role to make sure these things were getting done on time and on budget.

This next part is really just for Professor Gensler's benefit. But I find it fascinating. One of the things that stands out from Vannevar Bush's strategy was to use contracts rather than grants, let alone gifts, to make it look like these were equal partners entering into a business arrangement. I find this actually very fascinating.

So the last thing Vannevar Bush wanted would be anything like a federal takeover or a federal bailout of higher education, that universities should be independent from the federal government. And so instead, if it looked like two equal partners coming to do business together, like in the private sector, we'll have contracts with overhead and all these kinds of affordances of a business-to-business style contract as opposed to a grant or a gift or things like that.

So in actual fact, the universities were completely desperate for funds. This was now nearly a decade into the Great Depression. All of these universities were facing enormously difficult financial times. But Bush wanted to maintain the appearance of equal partners arranging contracts as opposed to anything else. I find that really interesting.

OK, so what's going on then at MIT? Here's a photograph from the top. There was rooftop facility temporarily built not just in building 20, but even in part of the Infinite Corridor. This was now on the roof of building 4, part of the Infinite Corridor there. So they had many, many sites on campus.

So the Rad Lab grew very, very quickly. It began once the green light was given and they could throw that plywood palace together, building 20. They began attracting staff to it. At first, they hired 30 physicists, most of whom were not previously at MIT. They came from other universities across the country.

They had three security guards-- this was a top-secret effort right in the middle of campus-- two stockroom clerks and one administrative secretary, not so big. It was led by a nuclear physicist, not an engineer or even an electromagnetic expert. The physicist, Lee DuBridge, who at the time was at Rochester University in upstate New York, he was recruited to temporarily leave his job and move to MIT to be the scientific director for this.

But it quickly grew well beyond physics or even electrical engineering. It included meteorology, experts in geology, what we've now called material science, even linguistics. How do you how do you identify signal from noise and so on? It grew very rapidly.

In fact, after less than two years of operation, the staff numbered 2,000, not just 30. And it doubled again before the end of the war. So by the end of the war, it had 500 academic physicists, a very large fraction of all the PhD physicists in American universities altogether, a huge fraction were recruited to the Rad Lab.

It was, by this point, spending $1 million per month. If you adjust for inflation to our contemporary currency, that's about a $15 million per month budget. They were burning through cash very rapidly.

And this became the largest part of actually a very large suite of defense projects that were being done at MIT throughout the war totaling, again, in today's dollars, about $1.5 billion. MIT became, by a very, very wide margin, the single largest University contractor for war-time projects in the United States. And in fact, it was even a bigger contractor for these research and development projects than some of the largest industrial companies in the country, AT&T, General Electric, RCA, DuPont, Westinghouse.

The research and development contracts from the OSRD that came to MIT were three times more than even those huge industrial behemoths. Now, those companies got huge contracts for production like building airplanes and engines and all the rest. But the actual R&D, MIT became an enormous, enormous node of this OSRD.

So the Rad Lab staff-- now, they had 4,000 people by late stages in the war, they were very busy. They designed dozens of different radar systems, not just one type of system from that one cavity magnetron, but really dozens of variations. So you wanted to have, say, ground to air to get early warning about aircraft, air to sea, ground to sea and so on.

Now, these were all in the centimeter range, a couple of centimeters. So they were of that new type, but now adapted to different kinds of tactical needs. They would conduct tests, literally from MIT rooftops, to see if their beta versions could detect actual aircraft from nearby airports, what are now the Hanscom Air Force base in the western suburbs and what's now called Logan Airport, both Air Force and commercial aircraft.

And they also trained nearly 10,000 active duty service members from across the United States. They would come to campus for very brief, very intense training in how to use these new systems and then be shipped out and use them operationally.

Now, at first, many of the theoretical physicists who were recruited to the Rad Lab, they were, even by their own lights, pretty arrogant. That's not just me saying so. Many of them came to that conclusion themselves.

After all, they came in saying, oh, radar. That's just classical physics. That's merely Maxwell's equations. How hard could that be?

Many of them had been immersed in these very fancy, esoteric ideas about quantum theory or nuclear physics of the sort we've talked about in recent sessions here. They were quickly schooled. They learned very quickly that calculating the actual electromagnetic field configurations for real devices, not just the kind that they assign to their students on problem sets, was as we physicists say, non-trivial. Means it was really, really hard. This was not at all an easy task.

So as you all know and are still learning, as we still use in our own more mature research, oftentimes, it's very, very important and very helpful to exploit symmetries to simplify calculations, imagine a spherical symmetry, or if you really must, a cylindrical symmetry, so two dimensions of space can be treated the same way, and one third one's different. That was going to get you absolutely nowhere when it came to these real-world devices like radar.

Here's an example of just some of the so-called components, these waveguide components, that were already in standard use by this time, by the mid 1940s. Few of these could be treated as a cylinder. None of them could be treated as a sphere. And these are just components. The actual parts of these radar devices, like, here's one schematic, would be putting all these together in these complicated forms. There is no symmetry argument is going to help you there.

So what the physicists began to learn-- and again, many of them recalled this years afterwards-- was really a whole new way to think about their own calculations. And here, many of them credited the engineers-- with whom they were suddenly and often for the first time working very closely-- credit to the engineers for helping them to learn a whole new way to think about their own calculations, to think about effective circuits don't start from individual basic parts, and even more basically, focus on input output relationships.

So you might have a particular circuit for part of that radar system that would have a bunch of resistors, some in parallel, some in series. You have capacitors. You have all these messy electronic components. And although it is the case that one can simplify these mathematically and find an effective circuit using things like Ohm's law, the engineers would say, don't even waste your chalkboard time on that.

Stick a lead on over here. Stick a lead on over here. What's the current flowing in? What's the current flowing out? Infer an effective overall resistance.

Have an effective circuit based on the input and the output. And stop it. You don't have time to do this kind of thing, plus when you're faced with those crazy, crazy shaped waveguides, even these simplifying mathematics would be no help.

So several physicists, including this gentleman here, Julian Schwinger, who spent the war working at the Rad Lab, they later recalled that this new approach to this engineering input-output approach to problem solving really shaped how they thought about research questions even after the war was over. And that's a little bit of a foreshadowing. We'll look at some of the lessons that Schwinger took from his radar experience when he returned to challenges in quantum theory. We'll look at that in a few class sessions.

OK, so by 1943, so in roughly 2 and 1/2, three years into kind of full scale operations for the Rad Lab, these kinds of units were actually developed and deployed all over the so-called theaters of battle. They were not only used in ground-based scanning stations. They were also put onboard aircraft, onboard Naval vessels.

They began finally to turn the tide against the devastating German submarines, the U-boat campaigns, as well as the Luftwaffe bombing raids over Britain. It turns out these systems were not only, in some sense, defensive. It wasn't only trying to get early warning of an incoming attack, though they turned out to be very effective at that. These also became very important for offensive weapons, for weapons that would go and attack the enemy.

And so one of the most substantial was actually a related OSRD project, the so-called Applied Physics Laboratory associated with Johns Hopkins University near Baltimore, which was set up in a similar fashion to MIT's Rad Lab. And one of the most important things there was developing the proximity fuse. So this would actually embed-- it was really quite amazing-- embed miniature radar units in the warheads, in the tips of these artillery shells.

So now each artillery shell that would be fired from these very large cannons would carry its own ranging device. So it could tell in real time how close it was getting to a given target. So you could then wire these things up to explode, to actually detonate, not any old time, but only when they were within some preset distance from the target. And that had an enormous impact on the offense.

Previously, these anti-aircraft efforts, like shooting these big guns from a Naval vessel against incoming aircraft, they typically had to fire hundreds of rounds, these very expensive rounds, to hit a single fast-moving airplane. They had a very bad return on investment, so to speak. They were not very effective. Once these same shells now were equipped with these proximity fuses, they needed on average two, not hundreds, to successfully strike an incoming aircraft.

So after the war, it became common, especially for veterans of the Rad Lab of the Applied Physics lab, to say that nuclear weapons of the sort that we'll talk about for the rest of today and on the film, that these weapons might have ended the war. But it was radar, they said, that had won the war. So let me pause there and take some questions. I see the chat is filling up.

So Fisher's right. So building 20 is indeed on the campus location where the Stata Center now is. And whether that's an ugly building or a beautiful building, we can all decide. But indeed-- it's a building of real legend. It was really supposed to last five years. And it was in constant use for 55 years, much beloved.

There's a time capsule within Stata, so on the same physical location-- when we can all get back on campus, I encourage you to go take a look at it for those of you who might, like me, still be remote. There's a time capsule in Stata of Rad Lab materials and memorabilia. They wanted to have it on the same physical site. And it will be sealed until sometime later in the 21st century.

And so anyway, so that's a large part of MIT'S role and kind of legacy during the Second World War. So Hastens asks, how is the original radar built if it was so non-trivial? Yeah, good, so the non-trivial part was mostly shrinking it down to short wavelengths and having a means of generating high power, high intensity waves of that short wavelength, and also getting very careful electronics to detect the echo, getting even fancier electronics to detect any kind of frequency shift, the Doppler shift. The original idea of getting a big basically a big radio tower, send out large multi-meter wavelength waves, people had been generating radio frequency waves since around 1900, the 1890s. Think about Marconi and other people.

So just generating long wavelength radial waves and detecting them, that's kind of like what radio does. You have to have a little more sensitivity to get the right radar echo and get the timing right. But that part was indeed close to a kind of trial and error, or let's say, building on established engineering principles. But getting it really to work with short wavelengths, much finer resolution both for time and frequency. That was much more tricky.

Gary tells us that his own father was experienced in the war. He was, say, a mere corporal. Yeah, so he found himself-- because you're getting ahead of ourselves here. So Gary, we'll see photographs of the sorts of experiences your father indeed might have had, and also, more in the film as well.

By the way, much like Gary is reminding us of, there was a large number of people who were stationed at places like Los Alamos and other Manhattan Project sites who were part of what was called the SED, the Special Engineering Detachment. These were people who were drafted. They were not recruited especially for the scientific project. Many of them had a high school level education, had some aptitude for physics and math, but were not full-time science students or engineering students.

But if they had any aptitude with using their hands, radio kits and so on, many of them were sent to the special engineering detachment to these high-powered labs. And that's where many of them got their first kind of real exposure to higher level kind of laboratory work. And several of them then decided to-- it changed their life path. And many of them then decided to go and study these topics more formally in graduate school to get a PhD to become professors, when before that, they had never dreamed of such things. So that SED detachment played a largely kind of unsung role at a lot of these wartime laboratories.

So Alex is right. So not only, by the way, were the proximity fuses so secret. He's absolutely right. They could only be fired over the open water in the beginning. They relaxed that by the end of the war.

But the fear was if one of these failed to detonate and it landed on the ground, could the enemy troops capture it and then reverse engineer it? So exactly as Alex very rightly reminds us, these proximity fuses, especially in the early rounds, literally rounds, were limited only to Naval operations so if it didn't explode, the enemy couldn't capture it. I think is just extraordinary.

Fisher asked, what was the status of radar in Germany? They had some prototypes. Yeah, that's right. So again, that's one of the places where there had been early working units, even before the start of the Second World War in the '30s. There were, again, efforts to improve them. But much like we saw in Monday's class, everyone, especially the Germans, thought that Germany would win the war immediately. The blitzkrieg was just blindingly successful in the early months and years.

So they figured, why bother sinking a lot of research? The one exception to that by the way, was peenemunde, the effort to develop rockets. That really was invested in very heavily. And, of course, it did have a real impact, even during the war itself.

But for a lot of these other high technology, wartime projects, the Germans tended not to invest so heavily because they thought they'd win. And then when the tide turned, they said, oh, we're not winning. But now we have to divert resources to proven technologies. And then, yes, we also have Alex-- Alex reminds us we can also thank microwaves for burnt popcorn and so much more, like most of our lunches probably during the pandemic. Any other questions about radar or burnt lunches?

OK, let's switch gears now. Let me go back to sharing screen. These are great questions. Let's go back now and we will shift now to the other most famous project of the OSRD, the Manhattan Project.

So I do want to emphasize, over the course of the war, this Office of Scientific Research and Development with Vannevar Bush at its head oversaw literally thousands of defense projects for the military. It wasn't like there were only two or three. It wasn't just radar, proximity fuse, and Manhattan Project. There were literally thousands of funded projects.

The biggest though, the largest in terms of personnel and budget, and arguably, in terms of impact on the course of the war, were indeed radar and then the one we'll turn to now with the project for nuclear weapons. So this other main project was officially called the Manhattan Engineer District or the MED. Of course, it was rapidly shortened to just the nickname the Manhattan Project.

Why was it called the Manhattan Project? It actually started the first headquarters for the first very small planning office was in Manhattan. It was a joint project between this OSRD and the War Department, in particular the US Army Corps of Engineers, long-standing organization within the army.

And the Corps then as now has these regional offices. There's a Corps to oversee things around, say, the Mississippi River. There's a Corps office for the Northeast and so on. There's a regional structure for the Army Corps of Engineers, then as now.

And it was the Manhattan office that was made in charge of this early-on quite modest-scale effort to begin investigating fission for weapons purposes. So they were literally headquartered in New York City. And that wasn't entirely random.

Some of the earliest scientists consultants on this project were at Columbia University in New York City, including Enrico Fermi, who had just, as we saw last time, had just left Italy upon receiving his Nobel Prize in December of 1938. By January of 1939, he was then basically set up at Columbia and many of his colleagues there. So that's why it was called named for Manhattan.

Very, very quickly, this project grew well beyond that small little planning office. In fact, it included more than 30 sites across both the US and Canada. Over the course of the war, it wound up employing more than 125,000 people. It was a massive, massive project, far, far larger than radar in terms of personnel.

And of course, the overwhelming majority of those people, of those 125,000 people who were paid by the Manhattan Project during the war, most of them had almost no idea of what the project was actually about. There was a very, very tight control of information flow. And you'll hear more about that, even in the film, *Day After Trinity.*

So although these people were officially working on the Manhattan Project, very few of them had any idea about what the project was even aiming to do, let alone, the relevant details. So among these 30 sites, there are four that really were most critical to the project and that get talked about most often. And again, you'll hear more about these in the film. And those four are highlighted here on the map, Chicago, Illinois; Oak Ridge, Tennessee; Hanford, Washington; and Los Alamos, New Mexico. The film is largely about developments at Los Alamos, but it does give us insights into these other three main sites as well.

We're going to take a tour today at some of the-- a brief tour of some of the kinds of work that was being done at each of those four main sites during the war. We're going to start with Chicago. That installation, that part of this very large sprawling project, was called the metallurgical laboratory. They weren't doing metallurgy. These names were always meant to throw off suspicion.

It wasn't actually basically material science or chemistry. But they gave it a name the sound kind of innocuous. By this point, Fermi had moved from Columbia to the University of Chicago. He moved pretty rapidly upon emigrating to the US. And he was one of the main leaders then of the Chicago Met Lab, as it was known for short.

The Metallurgical Laboratory took the lead on trying to further understand these still-quite-new fission reactions. And that was what Fermi had been working on even before he even knew it, went back from his Rome days, and certainly one of his main interests once he arrived at Columbia. So the Met Lab was focusing on the physics and chemistry of fission.

One of the first things they did was build this monster here. It was known by the code name Chicago Pile One. You can see, it's literally a pile. This was the first working nuclear reactor in the world. It was built, as some of you may know, under the stadium seating of the Stagg Field stadium on campus.

There were underground squash courts, like racquetball courts. And they during the war, in secret, took over some of those underground facilities to start developing and building the first working nuclear reactor. No one above ground was told that they have a bunch of uranium underneath.

So what was their goal? Each time a uranium nucleus underwent fission, additional neutrons were released. This was not so obvious at first with the experiments from Hahn and Strassmann in Berlin. But this is exactly the thing that a lot of us based labs and elsewhere began to identify and then to confirm as soon as Niels Bohr arrived in New York and let his US-based colleagues hear about fission.

Once people began replicating the basic fission reaction in their labs, they could then hone in on the other reaction products. And so it was clear by Fermi's time at the Met Lab that more neutrons came out each time a single nucleus underwent fission. And that meant there was a prospect for getting a chain reaction.

If you inject one neutron into the system, if this nucleus splits and gives out more than one new neutron, each of those could split neighboring nuclei. Then would split more and more and more. It could become an exponential runaway process known as a chain reaction.

So what was this pile? How did this reactor work? It consisted of 57 layers. You can count them up. I'm not sure all 57 were there yet. But it was literally stack upon stack upon stack of very closely packed ingredients.

So most of the weight actually came from graphite bricks, dense carbon bricks. Those were not going to undergo fission themselves. They're not a nuclear source. They were actually to slow down the neutrons.

So each time a neutron flies out of one of these recently split nuclei, you want it to interact with some moderating material. And it turns out carbon was quite effective the carbon inside these graphite, not to absorb the neutron but to slow it down.

Remember, we saw Lise Meitner and Robert Frisch had recognized that fission reaction rates in general should rise if the neutron is slowed down, because then its quantum properties would be stretched out more to be comparable in size to the entire target nucleus. So the idea was to use some moderating material, some material that would slow down those neutrons by a few collisions, not to absorb them, so that by the time the neutron then found a neighboring uranium nucleus, it would be more likely to induce fission.

So most of these piles are the graphite moderators. In between, were little chunks of uranium metal, some of which would hopefully undergo these reactions. And the last and quite critical part of this were huge control rods, 14-foot-long rods of purified cadmium metal. Why cadmium?

The idea here was not to slow down the neutrons but to absorb them. So cadmium will very readily absorb neutrons. So if you want to halt a chain reaction from say, blowing up the entire University of Chicago, let alone the lovely sports arena here, if you want to slow down or halt a fission reaction, you start taking neutrons out of the equation. You absorb these neutrons before they can find a target nucleus.

So the graphite bricks moderate the energy of the neutrons. The cadmium control rods take them out of the system altogether. And then these were movable. They could literally be manually, in the earliest days, manually pushed in or pulled out to control the average number of neutrons in play.

And so with this arrangement, the very first self-sustaining chain reaction that got this reaction to undergo, not a runaway chain reaction, a controlled chain reaction, thanks to those cadmium rods . That went critical literally underneath the stands here on December 2nd, 1942 under Fermi's direction. That was not quite a full year after the surprise attack on Pearl Harbor.

So you can see, the pace begins to pick up very rapidly once the US did actually enter the war. The bombing of Pearl Harbor was December 7th, 1941, the so-called day that will live in infamy. And almost exactly a year later, Fermi's group in Chicago had produced the first self-sustaining chain reaction.

OK, now independent of that, kind of in parallel, there were developments going on at other sites which would also eventually become absorbed into the Manhattan Project. So another very important one was at Berkeley, California where a very young nuclear chemist who was an assistant professor, just a few years past his own PhD, named Glenn Seaborg, worked with a small team. He was a nuclear chemist. And they actually finally, finally succeeded in doing what Fermi had first thought he'd done back in the mid 1930s.

So Fermi, remember, we saw won the Nobel Prize for essentially a mistake. Everyone, including the Nobel committee, thought that Fermi had produced nuclei heavier than uranium by neutron capture, although it turns out, Fermi's group was inadvertently inducing fission. While Seaborg and his team actually finally, so to speak, was able to successfully produce transuranic nuclei with the same mechanism that everyone thought had been already been going on. They could control it better and measure the products better.

And so early on, he and his team produced neptunium by neutron capture followed by beta decay. And then a few months later, by very early 1941, Seaborg's team had produced the next largest element on this new extended periodic table, plutonium. This was actually a single neutron capture followed by double beta decay.

So the heavy uranium nucleus, one neutron undergoes beta decay so the proton count has increased by one. Then a second neutron within that same nucleus, will undergo beta decay. And now increase the proton number by another step. So now you've made element 94.

The next month after first making very small trace amounts of this new element, Seaborg and his colleague, Emilio Segre-- Segre had himself left Italy because of Mussolini. He'd been a member of Fermi's group in Rome. He relocated to Berkeley.

So the nuclear chemist Seaborg and the nuclear physicist Emilio Gray then began studying the properties of this brand new chemical element, plutonium and particularly found that plutonium really is subject to nuclear fission, much like certain isotopes of uranium. Within months after that, Seaborg then went to what was by now this flourishing Manhattan Project site, the Met Lab in Chicago, to work more directly with Fermi and to continue measuring the properties of plutonium and its fission rates. So that's largely what's going on at Chicago during this time.

Meanwhile, overseeing this entire project, the entire Manhattan Project, was a member of the Army Corps of Engineers, the US Brigadier General Leslie Groves. Until that time, Groves's largest project had been overseeing construction of the Pentagon building. Literally, the building itself was quite new by the late '30s, early 1940s. And Groves, who was an engineer, a rising member of the US Army Corps of Engineers, had been like the head contractor.

He'd overseen the construction of this enormous, enormous strategically important headquarters for the war department. So he was seen as someone who could get things done on budget. He was then tapped to take over this newest new project of the Manhattan Project.

And in fact, as again, you'll hear more about this in the film, Groves was very reluctant to do it. He actually was very eager to see combat. Once the US actually actively entered the Second World War, he wanted to be leading troops in battle. And he thought this very abstract-sounding weapons project, something about nuclear fission, if it were to work at all, would have some long-term benefit or impact much down the road. Groves was eager to see the scenes of battle directly.

Nonetheless, he was more or less ordered to take this over. And he was in the army. He followed his orders. So he was then put in charge of this entire project. One of the first maneuvers he did, which really just stunned, stunned people around him, was he asked the very young theoretical physicist at Berkeley, Robert Oppenheimer, to join Groves as the scientific director for this new Los Alamos laboratory.

And you'll hear a lot about Oppenheimer in the film. It actually functions as almost a biography of young Robert Oppenheimer combined with the story of these projects during the war. So I won't say too much now about Oppenheimer, but just to say this was a stunning move on Groves's part, stunning at the time.

So Los Alamos began operations. And in the spring of 1943, if you may remember, the project was established in June of '42. So just getting things like the Chicago lab up and running was really the earliest priority.

And by the spring then, by spring of 1943, not quite a year into this new project, this additional site, what would eventually become a kind of central coordinating site, at Los Alamos, New Mexico was set up, as you'll see in the film, taking over what had been a very tiny boys school, young like K through 12 Academy in rural New Mexico, with mud-caked small little facility. Oppenheimer used to enjoy vacationing in that region, going on long camping and horseback riding trips. So it was actually Oppenheimer who recommended the site to Groves, saying maybe we can requisition this out-of-the way place that could be well-hidden and kept secret.

So again, just a little bit about Oppenheimer. And here's the poster for the film that you can learn much, much more. There are many, many very, very good books about Oppenheimer, including this one that actually received the Pulitzer Prize. It's a spellbinding book as well as one based on an enormously impressive research.

Lots more to say about Oppenheimer, I'll just be brief. He was a near contemporary of people like Werner Heisenberg and Wolfgang Pauli. He was roughly two years younger than Heisenberg, so pretty similar generation. Oppenheimer was a bit of a prodigy. He actually went to Harvard very young. For his undergraduate studies, he had skipped grades as a younger student. And then he studied for his PhD in a quick postdoctoral jaunt in Europe, both in Cambridge, England and especially in Gottingen. He actually did his PhD under the direction of Max Born.

So he was there just as the brand new quantum theory, quantum mechanics was emerging. He got to meet many, many of those folks when he was a grad student there. He came back. He was hired to teach both at Berkeley and at Caltech.

He was hired to be a photon professor at two universities hundreds of miles apart. And both schools were so desperate to get him, they agreed to let him spend one semester at Berkeley and the next semester at Caltech. It was just extraordinary.

And part of his role, what they hoped he could do was build up a US-based strength in theoretical physics, which was seen, I think quite appropriately, quite accurately, as really lagging behind the European schools by that point. Before the war, he had basically no experience with either experiments or with any large-scale organizations, which is part of what made it so shocking when General Groves asked him to play this very large administrative role for the wartime projects.

OK, so as soon as this new facility at Los Alamos began to get built up, Oppenheimer's own former student, his postdoc, Robert Serber, gave a series of initiation lectures for the new recruits who had been asked to come to this place but not told why. It was so top secret, people were basically not told why they should drop everything and move to nowheresville rural New Mexico. So Serber gave what was actually called a quote, "indoctrination course," as if they were joining a cult.

There was another physicist, Edward Condon, who took notes and typed them up. And this 24-page document became literally the first technical report of the laboratory. It was classified immediately. It was a top-secret report. This was Los Alamos Report One, of which there would be thousands, in fact, probably tens of thousands then to follow.

Informally, it became known as the Los Alamos Primer. Decades later, it was declassified and published. And in fact, you can actually just download the PDF of the original TypeScript on the web. It's not hard to find.

So this is from the actual document, the actual primer. On page one, the first thing he tells these people when they meet together in Los Alamos is the following. "The object of the project is to produce a practical military weapon in the form of a bomb in which the energy is released by a fast neutron chain reaction in one or more of the materials known to show nuclear fission." Lest there be any doubt, basically, we are here to build bombs. That's literally the first thing he says in these notes.

The next thing he does is very, very quickly go over the back of the envelope order of magnitude estimates for the energy released every time a single nucleus undergoes fission exactly of that we saw last time that Lise Meitner and Robert Frisch had been doing not so long before and that work out in more detail in those lecture notes for Monday's class. There's one really interesting shift, though. I find this pretty fascinating.

Serber gets the same answer. But he chooses to write the energy associated with these nuclear reactions not in units associated with chemical or nuclear reactions like electron volts or maybe millions of electron volts. He writes down the energy in ergs. Remember, that's the unit of energy in the human-scale units, centimeters, grams, and seconds.

He's now not thinking about individual reactions among one or two nuclei. He's already thinking about a human scale because the next maneuver he does in these notes is say, this is not very much on a human scale. A fly buzzing around your head expends more energy than this.

However, that's for one nucleus that's undergone fission. There are 10 to the 25 nuclei in a single kilogram of this stuff. So suddenly, if you could get this runaway chain reaction that he refers to here, if you can get lots and lots of these nuclei each to undergo fission, they'll each release that amount of energy. Now you're talking about some enormous kind of reaction, not just one isolated nucleus that happened to fission, again, right on page of these notes.

The next thing he does is compare that kind of energy release with the energy associated with conventional chemical explosives like TNT or dynamite, basically. Those were well known to release something like 10 to the 16th ergs per ton not per kilogram of chemical explosive but per ton. So then, again, right on page one, he then takes this ratio to say, this is why we're people have gathered here in Los Alamos.

One kilogram of this stuff-- sorry, of a fissionable isotope would give off the energy equivalent of 20,000 tons of conventional explosives. Let me just pause here to say he's used a code here-- they were so worried about secrecy, even though they were in the middle of nowhere-- that in the notes, he never refers to uranium 235. He refers to substance 25. And the code was take last digit of the atomic number, so it's 92, the last digit of the atomic mass, five, that's your code.

So U-235 is 25. U-238 is 28. Plutonium is 49, because it's element 94 with atomic [INAUDIBLE] and so on. So that's what Serber writes on page is the reason to have brought all these people in secret to the mesa.

Now which material to use? By this point, there were several known fissionable materials. U-238 is actually mostly stable, as it had been clarified by this point. U-235 is the isotope of uranium that is most readily fissionable. However, it only exists in trace amounts in nature. So if you dig up Uranium ore out of the ground, whether in the African mines or in mines out in Western United States or elsewhere, most of the uranium that you'll dig up, the overwhelming majority will be this very stable isotope, U-238.

Less than 1% of naturally occurring uranium is of this fissionable kind. And in the meantime, this newest element that Seaborg and his colleagues had made, actually synthesized in the laboratory, plutonium, that can be even more fissionable under certain conditions. And yet, it existed only in micrograms, not kilograms. So these are the challenges that Serber begins telling the recruits.

This is, again, his hand-- actually, it's Edward Condon's hand-drawn chart, the chart that Serber showed. This is the level of detail and accuracy in the Los Alamos primer, literally taken from the primer. This is showing the reaction rates for fission in convenient units for these different types of materials.

And again, you can see here is uranium 235. Here's the common kind, U-238. Here's plutonium, the four and the nine.

So for slow neutrons of the sort that Meitner and Frisch were thinking about, ones that have been slowed by some moderator like in the Chicago pile, the highest reaction rate that had been measured at least was of uranium 235. The highest likelihood to undergo fission was way up here for 235. The problem was when the next nucleus fissions, the neutrons that come out of that are actually very fast. They're at these kind of nuclear energies or at least fractions of the nuclear energy. They're more up in this scale in a million times say electron volts or 10 million, not a tiny fraction.

For very fast neutrons, it turns out, plutonium is even more susceptible to fission than U-235. The challenge is, how do you isolate this trace stuff from this, because you want to get a lot of this stuff in one place, kilograms worth. Or how do you scale up this stuff by a factor of a billion from micrograms to kilograms? Neither of these seemed at all straightforward. That's where some of these other facilities then come in.

So we'll now look at the Oak Ridge facility very briefly, Oak Ridge in Tennessee. Here's an example of this enormous industrial scale operation under the auspices of the Manhattan Project, scaled up by the US Army Corps of Engineers and now with more and more industrial partners as well. This was literally a classified city. It wouldn't even show up on maps until many years after the end of the war.

And yet behind the fence, under classified conditions, they built the single largest factory at the time on the planet, the largest factory, at least, under one roof ever, with about a mile-- if you walk from here to here, the single building was more than a mile in distance. This was to try to separate the kind of uranium isotope that was now really needed the fissionable one from the common one.

Now, these are both atoms of uranium. So in terms of any chemical analysis, they will be indistinguishable. The chemical properties are the same. They're isotopes of a single chemical element. So people realized right away, and Serber lectured on this, of course, as well, to separate them, you have to turn to physical methods, not chemical ones. You have to exploit the very tiny percent level mass difference between this slightly lighter version of that more common isotope.

So here's an example I'll go through very quickly. There's a marvelous treatment of this by my friend and colleague Alex Wellerstein, who's a real expert on the wartime nuclear projects. You can check out his very brief essay there.

So here's what they wound up doing in this plant. Here's what's going on in this huge, enormous factory plant, something called gaseous diffusion. So you mix the uranium with fluorine to make a guess called uranium hexafluoride, U46. This is incredibly poisonous, incredibly noxious. It will burn through many kinds of gaskets and rubbers and metals. It was really nasty stuff to work with, not just to humans, but even to the kinds of engineering parts that one would build a factory out of. This was hard to work with.

Nonetheless, it had the property that they could heat it up. In equilibrium, the molecules of uranium hexafluoride that happens to include the rare, lighter isotope of uranium, those molecules would enter equilibrium with the more common molecules that happened to include the standard isotope, U-238. If they're in equilibrium, their energies should be about balance. The kinetic energy should be about equal.

But that means that the smaller mass here of the lighter isotope must be multiplying a slightly larger velocity, that the molecules with the stuff you want will, on average, have slightly larger speeds in equilibrium than the more common stuff. So put the whole gas under pressure, force it through these chambers with a permeable membrane, and then because you have a larger average velocity for the ones you want, for the lighter ones, they will diffuse through this chamber slightly more quickly.

So after a short amount of time, the ones you want, these small black dots, the ones with the fissionable isotope, will diffuse throughout the chamber a little bit faster than the ones that are stable that you don't want to focus on, not by a lot. The enrichment of doing this one cycle is less than 0.4% enrichment. And so the idea was, well, let's just do that 1,000 times, literally, scale it up like never before with the help of these experienced industrial partners.

And so what this building has is literally thousands of these cubic meter scale gaseous diffusion units strung one from the other take. You take the slightly enriched output from here and put it in another chamber and output and output and output. So you do this 1,000 times.

Meanwhile, the other main installation for the Manhattan Project was in Washington State at the Hanford site. And by the way, a member of our group here, Tiffany Nichols, is a real expert on Hanford. So we should get her to talk about Hanford sometime as well.

So Hanford, during the war, was also a secret facility, enormous, sprawling industrial site. Now here, the main partner was DuPont, although many other industrial partners there as well. And the job at Hanford was not, first and foremost, to separate the isotopes of uranium, but actually, to make more plutonium.

So their job was to take Fermi's Chicago pile, take the insights that people like nuclear chemists like Glenn Seaborg had learned in the interim, and do that at an industrial scale, build enormous reactors that could induce neutron capture within otherwise relatively stable uranium and then induce the production of plutonium. And so again, you can see the scale here. Just to put it in complex, there are multiple reactor complexes.

There was the B reactor, the F complex, and many others. All told during the war, Hanford required 1 billion cubic meters of concrete. Just think about the scale of that going on.

OK, let me pause there. So that's a kind of lightning tour of some of the technical things happening at the main Manhattan Project sites. And we'll talk more about what comes next. Let's see. So Fisher asked, by the time the transgenics were actually discovered, did people really know about antimatter or neutrinos?

Oh, good. Yes, good, so people had ideas, nothing like a real evidence yet. I'm going to bracket-- I won't spend too much time on that. But Fermi had actually done a lot of work creating a theory that included neutrinos and of the weak decay, more generally. But it was still entirely hypothetical.

And Fermi himself believed these particles would never be detected. He was very skeptical at the time. Will come to, actually, it turns out that the first evidence that neutrinos exist came from these huge nuclear projects, not during the war but soon afterwards.

So people had to build enormous industrial scale reactors or weapons to create lots and lots of these things flying out before there was any hope to try to detect them. And so we can talk more about that. But the short answer is, people had ideas about what we would now call neutrinos and the beta reactions. But it was still quite fledgling.

Johan asks, was there widespread protest against it [INAUDIBLE]? Very good. It was part of what we should talk about, especially on Monday and thereafter. The short answer is no. If you say widespread protests, an unequivocal no, no way, no how, partly because these projects were all deeply, deeply classified.

Many of these sites literally weren't even on a map. You could not drive to the town of Oak Ridge. You wouldn't know it was there during the war, and same with Hanford and many other so-called atomic cities they were nicknamed afterwards. So that's part one.

Part two, what was going to happen with these things wasn't so clear. And we'll talk more about that soon. Part three, well, let me leave part three to our discussion. Johan, that's a fantastic question. And that's exactly what I want to be able to talk about, at least broach, both with the film and with our discussion on Monday, good.

Muriel shared a screenshot, excellent. Yes, Alex is right. So part of why Oak Ridge was sited where it was because it had already access to enormous, enormous sources of electricity. It was really just-- I mean, you saw the photos. There was a huge industrial output.

Sarah says, will we talk about radioactive contamination? We will. Yes, very good. So they did. Sarah asked, did people worry about radiation from these materials? Again, Sarah, it's a great, great question. They were aware of it. It becomes controversial, I have to say, who knew what when?

So even with hindsight and declassification and lots of more documentary evidence, it's unambiguously the case that many, many of these scientists and engineers knew there was something to think about radiation at the time. It's also unambiguously the case that they were quite cavalier, not just with themselves, but also, and I think even more shamefully, with all these workers at these huge industrial sites who were handling extremely dangerous materials with minimal safety precautions or even basic information.

There's actually a very there was a dissertation on that very topic by a grad student in our own department in the SDS program some decades ago, again, based largely on declassified documents and so on. So there was knowledge that this radiation existed, that it was harmful to humans. It wasn't clear exactly how harmful at which doses. But it was unambiguously harmful in general.

There were some precautions taken, but nothing like what would come later. So that's a huge, huge question that much more of which is learned actually after the weapons are used. There's a long-term longitudinal study of victims of the bombings in Japan, for example, that goes on for years. There are then other kinds of experiments and more controlled studies after the Second World War.

And so we will talk about that. There's a second film we'll watch together, a second documentary, we'll see in a few class sessions that looks much more directly at the broader environmental impacts, including radioactivity associated with these very, very messy projects. And by the way, just one more plug. I showed the book cover.

My friend and colleague, Kate Brown, who's now also a professor at MIT, wrote this really very compelling, very moving book called *Plutopia* on some of the longer-term impacts, not just during the 1940s but even afterwards, about these things. So that's a very important, very good question, Sarah. And we'll have a chance to talk a bit more about that.

Were these commitments binding? Good. No, so Johan asks, were people threatened if they chose to leave? No. And yet, there was literally one person, one person who left Los Alamos, Joseph Rotblat is his name, before the project was completed because of what he cited as moral concerns, goes back to Johan's question.

So it wasn't that it was impossible to imagine the consequences of these things. Some people did. Some people thought about it and kept working the project. Some people said, that's not my problem. Some people said, someone else would worry about it.

And one person at Los Alamos said, this is my problem. And I don't like it. And I'm leaving. He went on to found the Pugwash movement, among other things. So again, great question. We'll talk more about those things-- we'll have an opportunity to talk more about that soon.

Let me press on. I want to talk-- the last part of class is a bit more brief. But I don't want to run too long. So let me jump in to the next part. These are great, great questions. So last part is now, how do people actually construct a device that would explode? How do you make an actual weapon out of these esoteric-sounding things?

So this last part is actually making bombs, very briefly. We saw each time a single nucleus undergoes fission, a couple extra neutrons are released. The problem that also is right in Serber's initial primer, they knew this right from the spring of 1943, was that if you have too small a mass of this fissionable material, then on average, too many neutrons will be close to the edge.

And so they're more likely to diffuse right outside of the active region than to stick around and cause more fission. So you have something like a critical size. If you have a larger volume-- the same density, same properties, just more of it-- then on average, most of the time, a new neutron is released. It'll be more likely to encounter another target, another nucleus, rather than be close to the edge and kind of fly out and fizzle.

So this introduces the notion of a critical size. From there, you can then calculate a critical mass. There's a huge story here you can learn some more about in Peter Galison really fascinating book called *Image and Logic,* also this really amazing resource written by a team of historians and scientists, several of whom actually applied for and received top-secret clearance so they could actually read classified materials, even though what they wrote about it would then be subject to-- it could only be safe to release.

So you have some real insider experts who worked on this other book called*Critical Assembly.* And a portion of that team is Lillian Hoddeson, who wrote the main piece we read for today. So what was happening at Los Alamos was a series of hybrid computation, human, almost entirely women, volunteer computers.

They were usually the kind of wives of staff. So the people who were first hired were almost exclusively men to work at Los Alamos. We'll talk more about the kind of gender dynamics in the field around this time that we'll see that more squarely in a lecture or two.

So most of the people who were trained in science or engineering in the US in this time were men. Many of them were invited to relocate to Los Alamos with their families. So there were many spouses, mostly women spouses, who came along. And many of them were then able to pick up work at the lab as well as computers, that is the people were named computers.

They were usually using these handheld mechanical calculators, not programmable electronic machines. Those were just at the moment under development. So you have these kind of hybrid human machine computing teams that would break down complicated iterative calculations to try to do things like calculate the likelihood for a neutron to leave a region of active material or induce fission. Will it drift and diffuse outward or not?

So with this series of early what we could call a numerical simulation, but just painstakingly slow, the scientists were able to estimate the critical size above which you more likely to be in this regime than that. And that was about a radius of nine centimeters. If you had purified all fissionable U-235 and you had a sphere of radius nine centimeters, you'd be more likely to have that thing undergo runaway chain reaction rather than this loss of neutrons from diffusion.

That then, the size, translates to a mass because you have a constant density of the metal there. So the critical size was related to a critical mass of about 50kg, over 100 pounds of pure U-235 at a time when this existed in tiny trace amounts.

So what had already been figured out, and Serber lectures on this in the primer, is you can actually get by with a much smaller size. You could get by a size closer to this if you surround the active material, the fissionable material, with something called a tamper, a very heavy metal that is very inert to nuclear reactions. So it will neither absorb neutrons nor undergo fission.

It'll basically just act like a mirror and bounce those neutrons back in, a very heavy, very inert stable nucleus of which they had ideas of what there might be. That was called the tamper and just put that heavy metal around the active region. Then you're going to reflect these neutrons back in. You can shrink down by a factor of about three, this critical size. And then the critical mass becomes about kilogram scale, not tens or hundreds of kilograms.

So now the question is, how do you get this thing to actually undergo a runaway chain reaction? So now you know roughly how much stuff you need for that critical mass. How do you get it to undergo this very rapid energy-releasing response, shall we say, how do you get it to blow up?

So here again, all that was identified already from the primer. They knew about this very early. The idea was to get two subcritical pieces so you're not in danger of either of these pieces, the shaded regions here, undergoing a runaway chain reaction, each too small. Neutrons, on average, will diffuse out before they cause too many fissions.

So you get two subcritical pieces of this enriched fissionable material and literally shoot them together like from a musket, from a gun. So they knew they were existing army guns actually in use that could get muzzle speeds of projectiles that would correspond to, say, a tiny fraction of a second. The velocities were thousands of meters per second or centimeters per second, I guess, so they could get these two subcritical pieces to be jammed together to make one critical mass within a tiny fraction of a second.

You'd also need to actually induce then-- once they're together, you have to inject at least one neutron that can start this runaway chain reaction. They were already thinking about what are called initiators at the time of the primer. The idea was to actually have a natural alpha emitter, something that is naturally radioactive like radium or polonium, glue that onto one of these pieces, attach it to one of the projectiles, and have beryllium or some other target on the other piece. It would basically redoing Chadwick's experiment from which he identified neutrons.

If you have alpha particles smacking into some materials like beryllium, they will produce neutrons. So just do that really fast by gluing the two ingredients of Chadwick's experiment into these pieces in the middle of a bomb. I found that fascinating.

They were so confident about this method. I just find this mind-boggling. They were so confident, they literally never even tested it. The first time any device ever underwent a runaway chain reaction from this U-235 gun-method assembly was that it was used against a population in the Japanese city of Hiroshima. And you'll see, of course, much more about the actual use of the weapon and consequences in the film.

So the very first time a device like this was even exploded at all was actually in a military usage on October 6, 1945. Many of you might know, we just passed the 75th anniversary of these bombings this past summer. So here's what is now called the atomic dome.

For some reason, it's still not so clear, this one building near ground zero was mostly destroyed. And yet, this kind of dome structure, the skeletal girders of the dome survived. That's now called the atomic dome. It was actually a kind of industrial management hall in the middle of Hiroshima at the time, the not even testing it.

The other method was actually much, much more complicated. And again, you'll hear more about this in the film. And we can talk more about it soon too. This became a major challenge. And this is the subject of Lillian Hoddeson's piece that we read for today, the other kind of fissionable material, the material that was even more likely to fission than uranium, was this plutonium. But it had a spontaneous fission rate. This was a naturally unstable element. That's why it doesn't exist on its own on Earth.

So it is more likely to blow itself apart in something other than a runaway chain reaction faster than you can get two of those subcritical pieces to join. No matter what the muzzle velocity was, they came to recognize, only by summer of 1944, well past the start of the laboratory, that any of these assembly methods for this highly unstable plutonium would be too slow.

So again, as Hoddeson tells us in the reading, what they wound up doing was pursuing something called implosion. This became a really very, very significant technical challenge. It leads to all kinds of moral challenges as well. I don't want to downplay those. I just want to say what occupied many of these folks during this very hectic days of the war.

The idea was to then get a tiny little plutonium core, actually have it separated into tiny little subcritical pieces but near each other, surround that with a tamper, again, so reflect the neutrons back in, but then surround that with multiple kinds of conventional explosives. That were shaped into what became known as shaped charges. So you want to set up-- here's the plutonium fissionable stuff here. Surround it with different blocks that are shaped very intentionally with different burn rates.

So this kind of basically TNT, one kind of chemical explosive, would have a certain burn rate. You have a different burn rate here, and different burn rate here, so you could actually shape the ingoing wave into a spherically symmetric shock wave that goes in instead of going out. So you want it, with very high precision, induce an ingoing wave that will then crush the plutonium core so that all these subcritical pieces are condensed into a single critical mass even more quickly, much, much more quickly, than any of those kind of muzzle velocity methods of gun assembly. We can talk more about that. But that was what was the idea.

Now, that created a huge challenges, both theoretical and experimental. How do you calculate the appropriate shapes? How do you actually mix these materials to appropriate purity, lots and lots and lots of challenges there. Really, the leaders were not so confident this would work on its own. This they did a test of. This became known as the Trinity Test. The film that you'll watch before Monday is called *The Day After* Trinity. It's referring to this now-famous test called the Trinity test, which happened on July 16, 1945.

You can see, here's the test bomb about to be exploded after Norris Bradberry leaves the assembly. So this was arranged not too far from Los Alamos. Plutonium was so rare-- remember, there was just barely eking out kilograms worth after that entire industrial effort at Hanford-- that at first, the idea was to surround this test bomb in an enormous very thick steel container literally called jumbo.

They had to build a special railroad carrier just because this thing wouldn't fit on standard tracks and get it from where it was made, I think forged in like Pennsylvania, to get it to New Mexico ahead of time so that if the bomb didn't work as expected, they could scrape off this very rare plutonium and try again. In the end, they wound up not using it. But that just gives you an idea of how experimental this was.

Here's one of the rare color photographs of the Trinity test. It was so powerful, it fused the desert sand into glass. There was a special material that was dubbed trinitite, glass from the Trinity test, that covered the desert floor from the unleashing of these extraordinary forces.

So three weeks after that test, and just three days after the surprise bombing of Hiroshima, a bomb of that kind, nicknamed Fat Man, a plutonium implosion bomb, was then dropped on the Japanese city of Nagasaki. Again, we just passed the anniversary.

And you can see, just as a quick version here, there's much more we can talk about, the kind of impacts of this nuclear weapon on the city of there. So many, many more questions to think about of the sort we're already were beginning in the chat now. And I want to-- these are important and very difficult questions. And we're going to take our time with them on Monday.

Just some things to think about, when you do watch the film, what got people to work on this? Did their own motivations change over time? Why were these things used? How was the decision made to use these new weapons?

What really was the impact militarily or strategically on the course of the war as imagined then or now? How do people react beyond these projects once the secret was revealed and so on, many, many hard questions to ask about there. So I'll stop there.

Good, Alex shared some good resources here. Scott Manley series is indeed excellent. And also, I encourage you to go check out Alex Wallstein's blog as well, tons of stuff. So I'll pause there. Any final questions before we turn to our discussion together on Monday?

OK, I'll pause there. Please remember, paper two due this Friday. Good luck with the paper. Enjoy the film. It's a hard film. But I hope you'll appreciate the film, I should say. Watch that on your own.

And then for those who are interested and able to spare the time, we'll meet together at our usual Zoom link Monday at 1 PM Eastern. Take care everyone. See you soon.