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PROFESSOR: But the topic for today is a big topic and an interesting one. So there's a lot to say about it. So I guess we're going to want to get started on that, which is MIT in World War II. I asked you to read I believe three pieces, the Hunter Dupree article, four, right, Hunter Dupree, Debbie Douglas piece, "Science Analysts Frontier," and the cybernetics piece.

AUDIENCE: The Lily Kay too. It was on the copy I have.

PROFESSOR: Was the Lily Kay article on there?

AUDIENCE: There was no Lily Kay on there.

PROFESSOR: Well, maybe last year's syllabus. I think we took that one off for this year.

AUDIENCE: OK. I read more than you did this year. Nyeh, nyeh, nyeh, nah.

PROFESSOR: But that's a good one to add, as well in some ways. And the reason that I picked those four is-- and actually, I think they're quite interrelated. And some people kind of picked that up in the response papers. And I'll sort of underscore that a little more. In that one of them is about the overall kind of national science policy sorts of stuff. That's the Dupree article.

One of them is about how those changes affected life on campus here on a day-to-day basis. The Wiener one is about how those changes affected the core content of what people were doing on campus and the actual kinds of science and engineering that were going on, because cybernetics was very much a product of that time. And then "Science Analysts Frontier" is a sort of outcome of the end of the war, looking forward.

And all of those things I think have a big impact on the MIT that you experience today and the landscape of how science is funded and organized in this country that you'll experience, probably regardless of whether you go into a research career or a career in industry, certainly if you go into a career in research, how technology gets generated. So I just wanted to say a little bit by way of review and then go into some other things. And I have lots of pictures to show, to give it a little bit of texture.

So Hunter Dupree talks about what he calls the Great Instauration, which is actually was allusion to Bacon. And a few people comment on his distinction between the Baconian scientists who sort of engaged in the affairs of the world and the more Cartesian model of a scientist, who is sort of isolated in the laboratory in a purely intellectual space, and that's an interesting way to think about this whole thing, and how these things sort of formulated in the years leading up to the Second World War.

What is the generally accepted start of the Second World War? Anybody know? Just date-wise? Yeah?

AUDIENCE: Was it August 1939?

PROFESSOR: Close. Within a month, September 1939.

AUDIENCE: The first day of September.

PROFESSOR: What happens in September 1939?

AUDIENCE: [INAUDIBLE].

PROFESSOR: Sorry.

AUDIENCE: Nazi invasion.

PROFESSOR: Yeah. Nazi invasion of Poland. That's the sort of generally accepted moment, although there's the Spanish Civil War before that and what not. When does the US get into the war?

AUDIENCE: December 7, 1941.

PROFESSOR: December 7, 1941, Pearl Harbor, more than two years later. A very long period, where Europe and most of Asia is at war and the US is not only not as the war-- it's not like when we get into it, there are a lot of people who really don't want us too and think we should stay out, Charles Lindbergh among them. And so this is this kind of limbo period where-- and it's actually in a way the same as in the first world war. The US is very late getting into it and has a lot of time to prepare.

If the US had gotten into the war in September 1939, we would have been a lot of trouble. There was nothing. There was no military to speak of in a sense.

Whereas by December 1941, things had been gearing up for a while. And that's this period where not only does Bush get interested and involved, but also the predecessor is-- there's this very interesting, sort of curious committee called the Scientific Aids to Learning, that is done under the National Academy of Sciences, which includes Vannevar Bush, James Bryant Conant, who's is the president of Harvard, a chemist, and also Frank Jewett, who we've mentioned before, who is an MIT graduate. He taught here. He is then head of Bell Labs, head of research for AT&T, and actually president of the National Academy of Sciences in the 1930s.

And these guys all get together on this sort of abstract study about-- anybody know what that refers to, Scientific Aids to Learning? It's a very modern topic in a way. How can we use new technology to help education? What are the new technologies they're talking about? LP records, 33 and 1/3 records-- does anybody know what a record is? LP records, 16 millimeter film, to some degree 35 millimeter photography, these are all the cutting edge media technologies in 1939.

And there are people saying, gee, there must be way to improve education using these things. And it's interesting when you think about-- we may have mentioned this before. We'll certainly mention it later-- Vannevar Bush's great paper, "As We May Think," where he introduces this idea of the memex, which is very much credited as being a kind of predecessor to the World Wide Web, so right about this time period. So he's got exposure to these sort of media film technologies at the

time.

And in the course of that committee, these guys get together and they think there's really something happening. The United States is generally mobilizing. Even though there's a lot of political debate, people really see that the US needs to build up the military during this period. And it's not at all clear that the scientific talent of the country is going to be utilized in the best way. And a lot of people, and we talked about this, during World War I felt that it really wasn't utilized in the most effective way.

And Dupree talks about, there's a lot of different options for ways that you might bring either scientists, to use that term generally, or people like you, to bear on the war effort. What might those ways be? What are the different options you might have? Well, one option is to just draft you all, send you into the military, and then I've got lots of smart MIT people working in the army.

Especially the army in 1940, you'd probably spent a lot of time peeling potatoes. You'd probably get handed a rifle and told to run into the machine gun fire. I'm going to draft you and rather than you being sent to the front, I'm going to send to the Watertown Arsenal to make guns or to help engineer the manufacture of guns. OK, you go work for the government, you work in a government facility, and you help with some important job.

That's not a bad way to do it actually. But you end up working on things that are already existing. And so there are labs internal to the government. The Navy has them. The Army has them. Even the Army Air Force had some stuff like that.

But they were generally seen as not the most cutting edge. And there's a lot of truth to be said to that. They were sort of concerned with building weapons that they had built for a long time, not really very good at dealing with things like electronics or other new things, and very, very hard for them to think about stuff that was outside the box.

If you were in the Navy, the Navy had a great cadre of people who knew how to

build warships because they built best warships and that's all they did. But outside of building warships, it was very hard to think about what you might do. Because that's what the Navy did, was they built warships, to some degree airplanes, mostly warships and submarines.

You could send all the scientists and engineers into industrial labs and have them work in industry and close down the school. You could organize a separate corps, where you say-- actually there are some things like this today. There's the Public Health Service. There's the NOAA corps, which is the oceanographic corp. These are sort of little quasi-military organizations that are peppered around the government.

You could say let's have a government-- well, there's a Peace Corps. I'm sure you've heard of that. You could have the War Corps.

And a lot of different options there for organizing. And these guys started to become worried that they didn't think that left to its own devices, it was going to go the right way. And so Bush and his group, particularly Bush in using his political connections, gets them to create this thing called the National Defense Research Committee. And he writes this famous memo that Dupree talks about, in June of 1940, which happens to be-- anybody know that picture is? What happens in June 1940?

AUDIENCE: Germans take France.

PROFESSOR: Right. France falls to the Nazis. So this is what, about less than a year after the war starts. And here you have Hitler walking down-- there's Hitler right there, Albert Speer, by the way, right there, touring Paris. And that's a pretty shocking image for the West to see. And it was a time of doom and gloom. A time of really the sense that if the US didn't get off its rear end and start doing things, bad things were going to happen. And you also have the Battle of Britain.

And the Battle of Britain refers, of course, the Nazi-- they were next going to invade England. But Hitler wouldn't do it until Goering could give him air superiority. And so

they started going over and bombing and preparing the ground. And they never quite got air superiority, because of the Spitfires and the Hurricanes and all this, not least of it aided by radar. And so in the spring of 1940, into the summer of 1940, is what they call the Blitz in London. I'm sure if you've been to London, you've seen that stuff.

Not only is there this sense of military emergency, but there's this sense that a lot of the danger is coming from the sky. And we really don't know how to shoot down airplanes and we don't know how to combat airplanes. And there's this sense of defense that is not being taken up.

And so these guys from the Scientific Aids to Learning, and this memo that Bush writes, particularly concerned about anti-aircraft defenses-- and Harry Hopkins, who is the chief of staff for the president, basically puts this memo in front of him. And he writes across it, OK, FDR. And that's the letter.

And with that letter, in the government world, if you have that signature on your letter you can pretty much do anything you want. It's literally like a blank check. And Bush goes around in the summer of 1940 collecting all these people to work in this National Defense Research Committee. And they divided up initially-- it's later called the OSRD. And it's a little bit confusing the way the terminology works.

But they divided up into different divisions. There's a division for transport and communication; aircraft, submarines, and mine defense; guns, projectiles, and armor; and bombs, fuels, gases, and chemistry. And these tend to be things that are not things that they feel are being addressed adequately through the services.

What's the one thing they leave out, by the way? They don't go near, they don't touch it? Aviation. They feel that the NACA, which Bush has then been chair of, the predecessor to NASA has aviation sewed up.

AUDIENCE: Is fire control listed there?

PROFESSOR: Fire control is under guns, projectiles, armor, and materials.

And so what they do in a sense is they grab onto all of the technologies that don't fit neatly into the services, the military services. And you'll see this again when we talk about DARPA. Because the Navy knows how to build ships. They're not going to tell the Navy how to build ships. But the Navy doesn't know the first thing about radar, and they're not particularly good at radio, and they certainly don't think very much about other sorts of things.

There's this great quote. I don't know if it's in that reading, from Bush, where he says, there were those who protested that the action of setting up the NDRC was an end run. A grab by which a small company of scientists and engineers, acting outside established channels, got hold of the authority and money for the program of developing new weapons. So they met a lot of resistance, particularly from the military itself, saying why are you guys doing this?

And Bush says, that's in fact exactly what it was. It was an end run. They went around all the established people. There are millions and millions of dollars flowing into Navy laboratories, flowing into other things, but building very traditional weapons and things along the lines that they didn't feel were going to be really thinking differently.

So they set this thing up. It's outside the Army. It's outside the Navy. And you have no idea what a bureaucracy is like until you look at the Army or the Navy in 1940. These are organizations that have existed for hundreds of years practically, or at least 150 years at that point. There was not a lot of rapid change going on, except maybe in the air arm in the Army.

And they bring these people on who can actually understand, who can manage the research and pretty much write checks with government money, with a handshake. This is not the NSF, where you have to go through peer review and you have to get your program approved and all the sort of things that a lot of people here on campus do today. This is like, show up at somebody's lab, ask them if they'd like to be involved? And the next thing they know, they got a check for \$250,000, which in 1940 is a lot of money for scientist.

And one of the things they really get right early on is this whole business about electronics and what role electronics could potentially play in the war effort. There's radar. There's computing. There's different kinds of systems integration. I'll talk more and I'll show you some pictures about proximity fuses and fire control and I'll mention radar.

And also of course, and Dupree mentions this, there's this uranium committee. Which is another one of these things that gee, it seems like it has potential. It's a bunch of pointy-headed scientists telling us some abstract thing that could be the greatest ever, but what do they know? These are like Hungarian physicists, who just have this idea on a blackboard.

And this uranium committee had sort of existed. But the Army didn't really own it. The Navy didn't really own it. And of course it belongs then, it gets folded into the NDRC. What does it become?

AUDIENCE: The Manhattan Project.

PROFESSOR: The Manhattan Project. Then it actually branches out of NDRC.

For a grant from the NSF. And say I want to get \$100,000, how much do I need to get from the NSF? Anybody know what the overhead rate is? It's like-- and I'll get this within 5% because I don't follow it every year-- it's like 63 and 1/2%.

So if I want to get a grant, any faculty member you work with that goes to the NSF and needs \$100,000 to do the work, I have to get \$163,500. And that \$63,500 from the top, just goes right off the top into MIT's bank account. And the reason I ask if you've heard about it, because a lot of faculty complain about it a lot because it feels kind of painful.

And what does it do? Theoretically, it goes to pay for keeping the lights, on keeping the heat on, somebody to come in and sweep the lab out at night, all the different things, the paperwork, that it takes to actually run these grants. And it is expensive to do that.

And most faculty see it as a big burden because gee, my \$63,500 which the NSF gave me, suddenly gets taken as rent by my landlord. And what do I get in return? All I do is get somebody who comes in to sweep the floor and it sounds like a lot of money. And Dupree really tells you why that was so important. And it was invented in this month, pretty much.

And it was one of the most critical ideas of getting all this stuff to work so impressively, which was-- MIT's total research budget in 1940, before this started, was on the order of \$300,000, the entire research budget for the entire Institute. I wrote the number down here. Well, in total MIT got from the NDRC, \$116 million. \$116 million, even in today's world, is a lot of research. And what does that mean? It mostly means people and desks and laboratories and all that stuff.

If MIT had to pay for building all those buildings and building all those desks and building all that heating and all that infrastructure, it have bankrupted the Institute by the time it got to \$3 million. But they added this overhead charge on there so that any time money came for research to hire post-docs or research assistants or technicians or other people, it came with this overhead. That meant that the dollar figure could grow infinitely large, infinitely large.

And again, think about that \$300,000 to \$116 million in under five years. We wish we saw that kind of growth now. And it was only able to happen because they built into this idea of the research contract, this notion of indirect costs. It was really a very fundamental thing that we still live with today.

That means that if I as a faculty member went to DARPA and I got \$100 million contract, MIT could support it. And they might have to build me a building, which happens all the time, you see these buildings around here. But they could actually do it.

The other thing about it was all of the research contracts, the military, the only thing they knew how to do up until then was to buy stuff. It's called procurement. It's still something they do a lot of. So if I wanted to do an experimental radar set, the only way I had to do it was to come to MIT and go, we'd like to buy 10 radar sets. And

we probably won't even use them and they may not even work, but at least we'll have a contract that has a procurement.

And what they invented during this period also with this R&D contract, where MIT doesn't deliver anything other than promising to put out its best effort to do the research and hopefully publish some papers on it. That was also a pretty revolutionary idea in that point. Until that point, there was no way for the government to do that.

So here's what Dupree says about it. It's a nice little sentence that captures it all. The contract was the device by which universities and industrial research labs were preserved as institutions, even while their social role was radically changed. I mean this was very much the vision that people like Bush and Conant had, was we want to keep MIT for what it is, keep it as the character that it has.

Obviously, it changed during the war in some basic ways. But it didn't change permanently in some sense. Where there's a free flow of ideas, there's an open flow of ideas. But I haven't addressed all these other kinds of problems. Without becoming part of the Army, or without it becoming part of the Navy, or having just everybody drafted and closing the place down for five years.

So the NDRC is created in June of 1940. It gets up and running. It starts to issue its first contracts in September, October of 1940. I'll talk about the radiation lab in a couple minutes when I show the slides.

Well, it's worth knowing that they get started under the NDRC in October, I believe, of 1940. They deliver their first radar set in March of the following year. So think about the turnaround there, to take a completely new technology and to deliver something the military can use in the field in four months. It was a pretty remarkable turn-around.

And in fact, some people in their response papers mentioned the intensity of the environment that sort of developed around here during that period. And commenting, a couple people, that it was hard to imagine it was any more intense

than it is today. Although it probably was.

And one thing that wasn't really captured in the readings is why it was so intense? What was it that was driving people to work such long hours and put such incredible time in? Again, most of the people doing this work are people just like you. They're either students or just recent graduates who are occupying these labs. Especially for the men, what happens to all your friends?

AUDIENCE: Going and getting drafted.

PROFESSOR: Well, what are all your friends doing?

AUDIENCE: Getting drafted.

PROFESSOR: Either getting drafted or signing up. It's not that the people who are working in the labs are trying to avoid getting drafted. That's more of a product of later wars. They're exempted from the draft because they're doing critical work.

And there's a lot of social pressure about not shirking your service. So it can be seen as a kind of embarrassment to be exempted from the draft to do laboratory work. It's a sort of cushy assignment. It's the sort of thing that people like Dick Cheney and George Bush were criticized for during presidential campaigns. All your friends are going off to war and you're staying home in Cambridge, working at MIT.

A lot of I think the motivation for people was they really wanted to prove they were doing something important and making a contribution to the war effort and not just avoiding the draft. Because they were exempted from the draft. And that they really were serving their country in the same kind of way. This was not the Vietnam War, which was very contentious about who went and who didn't go and who wanted to get drafted.

This was where the entire country literally mobilized. And everybody's job, everybody's home life, everybody moved around. And it really fundamentally changed the country for that period. So you have this environment inside the laboratories which is very different.

So a couple of statistics, as I mentioned MIT was the single largest recipient of OSRD already funds, I think by a factor of two or three, \$116 million over five years. Again, that's a lot of money in today's world, much less in 1940 dollars, where the total budget was \$300,000 before then. There were about 2,300 contracts overall in the OSRD, totaling \$500 million. So MIT got more than 20% of the total funds. It was a bit of an inside job, no doubt about it.

The Radiation Laboratory by 1942, again it was only founded in the end of 1940, so within a year it was as large as the rest of MIT all together. And it was of course, right there. The overhead started out as 30% and got reduced down to 10%-- again today it's 63 and 1/2%-- because they didn't want to be seen as raking off all this cash that came in.

And again, there was a lot of resistance. There's a great quote by Harold Bowen, who was the head of the Naval Research Laboratory. He was an MIT graduate. He said-- he's coming from within the Navy-- those of us who had been working in applied science for years cannot be blamed for not always enthusiastically endorsing all the efforts of the Johnny-come-latelys who inevitably steam into Washington at the beginning of the war.

So that was how they viewed Vannevar Bush and all these scientists, was they were coming in. We've been working on radar. In fact, they did. The Naval Research Lab really invented radar.

And here comes Vannevar Bush, saying we're going to do it all at MIT. And in a certain way, taking it away from the Naval Research Lab. Very contentious stuff, lots of power politics going on. Also with AT&T. I'll talk about that a little bit in a minute.

Some of the other big benefactors, and I mention this because these places all still exist and may be places you'd come across, the Jet Propulsion Laboratory at Caltech-- anybody ever heard of that place? Founded right during this period. What do they do now?

AUDIENCE: Stuff for NASA.

PROFESSOR: Yeah, it's part of NASA. They do a lot of deep space probes. They did the Mars Rovers that you've read about. They do essentially nothing with jet propulsion. But they were founded, under the direction of Theodore von Karman, to do rocket research basically. There's a whole new institution out there created right about the same time, by the same thing.

The Applied Physics Lab at Johns Hopkins. Anybody ever hear of that lab? Also a big government lab, associated with the university. They do all kinds of interesting secret stuff. They do submarine tracking and they do a lot of space design and they build satellites. And in fact, the former head of NASA, Mike Griffin came out of there. And they were founded in the same period to develop the proximity fuse, which was a little radar device. It was built into an artillery shell. It was designed to explode when it came near an airplane.

So these are all places that still exist. A lot of these big government or quasi-government research labs exist.

Let me maybe turn to the slides. Any questions on any of that? I have a few more numbers about the Rad Lab radar.

AUDIENCE: I mean one of the things that comes out in the article by Debbie Douglas is that the significance of the microwave research here at MIT was it that allowed people to make radar units smaller. So what had existed before? You mentioned the Navy.

PROFESSOR: I think I have pictures of that.

AUDIENCE: OK, great.

PROFESSOR: So here's one example. This will become relevant when we talk about Apollo actually. Again, one of the big concerns was about gunfire control. And this is a device-- I may have mentioned this before. Did I show this picture before so far? I actually have two of these things in my office. I bought them on eBay for about \$25, still brand new in the box from 1945, when there were manufactured.

And this is a gun site for a guy, an anti-aircraft gunner, aboard a Naval ship. And

what it does is it's got two gyroscopes in it. And it has a little mirror and it automatically calculates the lead for the gunner. So if there's an airplane coming in and you've got to lead it by some amount in order to fire ahead of it, because it takes time for the bullets to get there, and it can be very hard to train people to do that, that's how you shoot skeet and stuff.

And what this thing does, is it just says, if you just put the cross-hairs in your site, on the actual airplane, it will automatically calculate the lead and sort of force your hands to lead the gun. And this was built by, not only by Charles Stark Draper in the Instrumentation Lab here, but also by Bob Siemens, who was one of his students, who then became second in command at NASA during the Apollo program. We'll talk about that. And was one of their first forays into gyroscopes, which then became really important during the Cold War and later. I keep pushing the wrong side of the mouse.

And this is actually how it worked. So you can see they can just see the site and it sort of forces the gunner, if he keep the cross-hair on the plane, to calculate the lead. And one of the reasons I show you this is that one of the real themes that runs through the work that gets done at MIT is not just the microwave physics itself, but the user interfaces for a lot of these things. And building on that work that we talked about with the differential analyzer, how you actually kind of match these systems to human performance is really one of the big themes in the research. And that sort of leads us obviously up through Wiener and cybernetics.

This is one of the divisions of the NDRC, which was devoted to fire control, which is that's the same issue about how do you aim these different kinds of guns? And I give you this list because I want to show you the combination of people who were here and the representatives from both industry and the government and then also in the world of computing. So just to give you a couple examples.

This guy here is Warren Weaver, who is one of the senior people at the Rockefeller Foundation, who funds Bush's differential analyzer. Also is the guy who invented the term "molecular biology." And so he comes from the kind of pre-World War II private

foundation world of science funding.

This is Preston Bassett, who is the president of the Sperry Gyroscope Company, which makes a lot of these kinds of control systems. Harold Hazen, who is a student of Bush, who writes the first paper on the theory of servomechanisms in 1934 and becomes dean of engineering at MIT. This guy here is George Stibitz. He invented the word "digital" and built all kinds of control computers out of telephone relays during the war.

This guy is Ivan Gettling. And I'll talk about him in a little bit. He did a lot of the early work on radar. And later on, was really the father of the GPS constellation, that we now use to navigate our cars. Karl Wildes, also an electrical engineering professor here at MIT. George Philbrick, who really kind of invented the analog computer, electrical analog computer. And we'll talk a little bit more about that in a minute.

So you have all these people sort of coming together on this problem. None of them had ever thought about this problem before in their entire careers. Which was sort of a benefit, right, because the Navy figured they knew how to do it and all these guys just sort of came in and did it in a different way, with some fresh ideas.

This is an electronic, analog electronic computer that they built. You see these two guys here looking through these sites. The actual electronics for the computer is here. And they follow an airplane with these optical sites. And then it actually has giant servos on the gun that actually point the gun to aim it in the right place and then fire it. So it's the beginning of a kind of integrated control system.

And anybody here ever hear the term "operational amplifier" or use an operational amplifier? It's one of the basic building blocks of modern electronics. It's sort of the basic feedback loop. Any of you take, what is it 6002, I think they probably do op amps in that course.

The first op amps are invented to go into this device. And the whole idea of a feedback amplifier being used to do addition and subtraction and multiplication and division and integration and differentiation, all comes out of this device, from again,

from the telephone company.

Again, we read about Wiener. Wiener is a sort of mathematical adviser to all these guys. The book that I assigned the intro for you is from 1948, *Cybernetics*. But as he talks about in there, really kind of the genesis of it was him thinking about anti-aircraft fire control during the Second World War. And of course, now we have the idea of cyberspace and cyber this, and my Sony Cyber-shot, and all this kind of stuff.

The basic ideas of a lot of this came from people like Norbert Wiener, working out not only the basic mathematics-- in fact, you can see them on the board here. If you read the rest of that book of *Cybernetics*, which is a lot of mathematics, a lot of it is the basic equations for what today you call signal processing or digital signal processing. It wasn't digital when he did it. But the whole idea of correlation and convolution and different kinds of filters and stuff is came out of there. Yup?

AUDIENCE: So actually I got curious and went onto Wikipedia and looked them up. Those equations are actually on Wikipedia under an article called the "Weiner filter."

PROFESSOR: Yeah. The Weiner filter is a sort of classic optimal filter that is a predecessor to the common filter, which is something that people use all the time today in design and control systems.

There's Building 20, which is the actual radiation lab. Let's see if we can orient ourselves to it. Well, I'll let you see if you can do it. What are you seeing there?

AUDIENCE: Is that Vassar Street?

PROFESSOR: Yeah. This is Vassar Street here.

AUDIENCE: Oh, wow. It's really big.

PROFESSOR: It's big. It was built in about four months. It lasted about 40 years, probably longer, 45 years. It was basically built like an army barracks. What's this right here? I think that's us.

AUDIENCE: That's where we are now.

PROFESSOR: Where we are right now. In fact, yeah.

AUDIENCE: Almost exactly.

PROFESSOR: What's this?

AUDIENCE: Swimming pool.

PROFESSOR: That's the alumni pool, which is right out the window, which was already built then. Everything that happened is built around that. And so here is the-- I'm not sure which building that is. That looks like one of the original main group buildings.

So there's the Rad Lab. You can see this huge loading dock. Lots of stuff going in and going out. These different kind of fingers. And all these wacky radar antennas up on the roof for experimental testing.

Does nobody know what was it-- it's still there today-- the Christian Science church downtown? If you go like to Boston Symphony Hall, there's a big plaza and there's a dome. Which before Boston was built up, that was one of the prominent features of the Boston skyline. That was the first microwave radar target in history, from a building at MIT, fired over and reflected off that dome.

This is just an image of the various labs. There's many of these different labs in the Rad Lab. And it's considered a kind of prototype of what a modern R&D lab could be set up like. You can see here, it's divided up. There's a receiver lab, an indicator antenna lab, a shielded room, a darkroom.

If you know the history of physics, you'll know a lot of-- Lee Dubridge was the head of it. I.I. Rabi is a famous Columbia physicist. Kenneth Bainbridge I think was a Nobel Prize winner. I'm not sure about that. Pollard later won the Nobel Prize. So lots of people, who later became very, very important, including people like Paul Samuelson, the Noble Prize winning economist here at MIT, that you might not expect.

So the Rad Lab gets started around this device, the cavity magnetron. Anybody seen something like this before? There's two places you might have seen it.

AUDIENCE: It's on the poster in Lab 7.

PROFESSOR: So three. It is on the poster in Lab 7. Very good. I forgot about that one. Where else?

AUDIENCE: The museum.

PROFESSOR: So there's one in the museum. One other place you might have seen it, knowing what MIT students might be like. If you ever take apart a microwave oven, you'll see one of these things inside there. In fact, that's kind of the only place you'll still find them.

So this device is only about this big. If you go to the museum, you'll see it. It's one of the 150 objects. And radar had been invented in the early '30s really. But it was pretty long-wave radar. I may have a picture of it. Yeah.

So this is pre-World War II radar. This is built by Western Electric, which is part of Bell Labs. And there's a couple of key things to notice about it. What do you notice about it? It's really big. Why is it big?

AUDIENCE: With long waves.

AUDIENCE: It's using relatively long wavelengths, in the sort of hundreds of megahertz wavelengths. You can see the antenna and all the wires for it on the left. And this is pretty much state of the art when the Rad Lab is founded.

And more or less, this is an American radar. But the British have a version of this that they used during the Battle of Britain, they call it Chain Home, that is able to detect attacking aircraft. And it does actually work in fact. In fact, the Pear Harbor attack was detected by one of these right radars, as SCR-268 268, before it happened, a couple hours before it happened.

But nobody really had any faith in the technology. And it was new. And people didn't

really understand it. And it was just a bunch of blips on the screen. And the warning that the radar station issued, was ignored. Tells you something about any technology needs to develop its own credibility and to have people believe in it. After that, they tended to believe in it, once it--

But it's a very big radar. It's pretty unwieldy. You can see, it probably didn't work very well in the rain, because the guys are all standing there outside, exposed, and the electronics are fairly exposed. He's just looking into an oscilloscope right there. That's a pre-World War II oscilloscope. It's the size of a Volkswagen practically. And you see he's looking in through just a darkened hood.

And the British, the problem was that for higher frequencies, it was that very hard to generate enough power, at what they call microwave frequencies, which is sort of centimeters and below, in the kind of high hundreds of megahertz up to several gigahertz range. And the British come up with this thing called a cavity magnetron. There it is.

And again, it's not a big device at all. But I'll show you the shape of it in a little bit. It's got a central hole and there's little resonators all around it, a very characteristic shape of what's inside there. You put that in a magnetic field and pump a very high voltage into it and it generates really large, very high-power microwaves.

And this has all kinds of advantages. But the key one is that it's just small and the antennas are small and it allows you to do all kinds of different things with it. But it implies a whole new kind of electronics. For example, you may be familiar with this, but microwaves at high powers don't really like to go through wires. They need to go through pipes. What are those pipes called? Anybody know?

AUDIENCE: Wave guides.

PROFESSOR: They're called wave guides, right. So you have to invent a whole new kind of wiring or plumbing. You literally plumb this kind of stuff through. And all that stuff didn't exist.

But what the British did was they built this. They figured out that it worked. And in

September of 1940, they were being bombed to smithereens by the Nazis on a regular basis. They were barely surviving the war effort. And they didn't have a big electronics industry. So it wasn't easy for them to contemplate how to manufacture this thing in large numbers.

So one scientist, his name was Sir Henry Tizard, he came over to the US on an ocean liner, exposed to Nazi submarines. And he brought one of these. Actually, I think he brought three of them in a trunk that he kept under his bed on the ocean liner. It was probably the most secret military technology of the war at the time. And he just brought it on this civilian liner, sort of wrapped up in his socks and underwear. That's exaggeration. I think he had a special box for it.

And he brought them. And he brought them to the government and said, we have this thing. And we want you to have it. And we want the Americans to figure it out. They actually intended for Bell Labs to deal with it. And they brought it to the NDRC and Bush sort of said, well, we'll bring this up to MIT. And they founded a lab about it.

That's what happens in October of 1940. And that's when the Radiation Lab is founded. And it's interesting, because Rabi is said to have taken it out. And people said to him, he said well, how does this thing actually work? And they said well, that's easy. It works just like a whistle. It's like an electronic whistle, because you put power into it and it generates a resonance.

And then Rabi looks up at it and he says, OK, well tell me how a whistle works? And nobody at the time could really explain to him how a whistle worked. But that's not a bad way to think about what the cavity magnetron does.

AUDIENCE: So are you implying that the establishment of the Rad Lab here really rested on the proposition that it's not what you know, but you know?

PROFESSOR: To some degree. And actually it should be said that of the three, I can't remember the exact number that came over, one of them went to Bell Labs. And they also did a lot of work in microwave radar during the war, but there was work enough to do

for everybody.

So this is an image-- I actually have a blown-up picture of this on the wall in my office, because one of the great things about the Rad Lab is that photography was kind of newly cheap at the time. And they documented a lot of the research with thousands and thousands of photographs. And years ago, I was working through some of those photographs at the MIT Museum and I said to Debbie Douglas, there's great pictures of daily life at MIT during World War II in the Rad Lab things, that are not the sort of PR photos you usually see about the Rad Lab. And then she took a bunch of those photos, and they're all beautiful four by five negatives, and blew them up and did a little art show of them.

And this is one which I really like. And I'll turn the lights off, if I can. Just generally you can see them better. That do anything? Nope. OK.

Just to look at them a little bit about life at MIT during the war, which Debbie's chapter does a nice job of describing. What can you observe from this image? Yep?

AUDIENCE: The really, really high waist lines.

PROFESSOR: OK, high waist lines.

AUDIENCE: God, who wears there pants up that high?

AUDIENCE: Both women.

PROFESSOR: There are women there. A lot of women worked at the Rad Lab, very, very mixed gender environment.

AUDIENCE: That would be sort of the scientific version of Rosie the Riveter in that sense. Lots of women go into the workforce doing this--

AUDIENCE: They were going to work as scientists or as other technicians.

PROFESSOR: Mostly as technicians and administrators. Actually, I'm not even aware of one that worked as a senior scientist or even an engineer. What else?

AUDIENCE: The facilities are not like-- I can see piping.

PROFESSOR: Yeah. So that's pretty much the inside of Building 20. That's what it looked like. It was literally built in a few weeks. What else?

This one just captures this, I think the sort of sense of the pace that the place must have had. You have a sense, everybody's busy. They're walking somewhere quickly. They're moving things around.

There's equipment coming across the hall. That is a microwave radar antenna. That's a pretty radical departure from the previous slide I showed you of what a radar antenna looked like. That you can imagine putting on board an airplane.

And there's also the two cigarettes there. These guys all sort of identically dressed. You get the sense it's a place where just things are moving fast, sort of like MIT today. It wouldn't be out of place that scene, in the Infinite Corridor between classes today.

Here is another image, a much more formal one obviously, of the steering committee of the Rad Lab. You see people in here, like I mentioned Ivan Getting, who is here, who later went on, as I mentioned, to sort of spun the GPS project.

Anybody know who that is right there? That's Jerry Weisner, who later became President Kennedy's science adviser and president of MIT. I think this is Lee Dubridge, who's the head of it. But again, a pretty informal environment. Part of the weekly meeting, another one.

This may be the first time here, and Debbie had mentioned in her article and a bunch you mentioned in your response papers, the secrecy that was going on. Now, these days if any of have ever worked in even a mild corporate lab, you probably have to wear a badge all the time. This was probably the first time people had to wear badges at MIT.

And this is what a badge looked like. It was a little button. It had your picture on it, your employee number, and allowed you to get into certain places and not into

other places.

Again, it was called the Radiation Laboratory for a reason. What was the reason?

AUDIENCE: Disguise.

PROFESSOR: To fool people into thinking it might be a nuclear physics laboratory. It was about radiation. But it was not called the radar-- well, the word "radar" wasn't even well recognized anyway at that point. But it tried to disguise it.

Again, as we mentioned, lots of women working in these labs. Probably a pretty different work environment than what people were used to. Even though we've talked about women at MIT before, not in these kind of numbers and this much involved in the technical work. This is just a page out of the yearbook that the Rad Lab produced, showing all the different kinds of things they did. It didn't come out that well in the slide here.

Another image, I love their images of this sort of electronic experimentation stuff. It has a sort of thrown together sense of the director's chair, an oscilloscope. What I find interesting is that a lot of the connectors on all these machines are still connectors you might use today, like a BMC connector. You still see those everywhere. And this is what it took to get this stuff up and running.

More pictures of the labs, in this case without people. So this is probably the radar that was shown before in that hallway photo and is one of the more famous products of the Rad Lab. It was called H2X.

And what H2X did was it allowed, if you were in a bomber-- the US and the British were bombing Germany on a regular basis during most of the war-- but they had this famous Norden bombsight, which would allow you to sight bombs. What was the problem with the Norden bombsight, anybody know? If it was cloudy, you couldn't use it. And if anybody's ever been to Germany or northern Europe, during eight months of the year it's pretty cloudy.

And what this is, is a microwave radar. Again, it's not just an advantage that the

antenna is small, but the wavelengths are small enough. You can see things that are very small, so you can make out a lot of detail. But you could actually fly over in cloud cover and map out a river and a city and all this stuff. And it allowed them to bomb with radar, either at night or in bad weather. It had a huge impact.

The other thing about H2X, it was very important. It's worth keeping in mind about radar, because you see this with other weapons projects. Almost any weapons project that got made during the war, that actually was designed to blow something up, it was very, very hard for it to have impact in the war because for one thing, to go from a prototype in October of 1940 through development and testing and production pretty much took the whole war. So there was basically one full product development cycle.

If you look at like the great airplanes of the Second World War, the B29, the B17, these were all finished by the time the war started and it still took them years to get into production. Whereas, if you had, a radar, you could basically make one of them, send it out in the field in one of a bombing raid of 1,000 bombers and make a difference. So radar had this leveraging effect, where you could use very, very small numbers of them and still have a big impact. Which any kind of gun, if you didn't make a gun in numbers of the tens of thousands, it was not going to have any impact on the war.

AUDIENCE: [INAUDIBLE].

PROFESSOR: Yep.

AUDIENCE: How long between the development of that product would it be then on plane?

PROFESSOR: In the case of the radiation lab, it would be weeks or months.

AUDIENCE: Weeks or months.

PROFESSOR: And actually, no small number of MIT engineers went in the field, made them work, went on bombing missions. A few of them were killed, literally taking these things in the field. Think about it any lab prototype you've ever made, it may be a little rickety

in terms of its robustness for being in the field. It takes a lot of engineering to go from there to a package that some soldier is going to take out of a box. They didn't always wait for that time. And they did send people directly from the Rad Lab into the field, to train the troops and help them get up to speed.

In fact, Karl Compton, the president of MIT, was not-- in a sense, Bush, before then, he was junior to Compton. He goes in and becomes head of the NDRC and is senior to him. Compton became head of what was called the Office of Field Service, where they did exactly that. They took all these things out and they helped people understand how to use them.

There's a B17 at Hanscom Field, right out in the suburbs here, where the Rad Lab had a station. And they would do a lot of testing and a lot of different experimentation and flight tests and stuff, also at Logan Airport. Here's a H2X installation inside a B17, to allow the radar operator to look through the sight.

And again, think about what a different kind of radar this is. The one I showed you from before, the prewar radar, they're basically soldiers on the battlefield, these guys. They're wearing helmets and they're very exposed.

Here, not only are you in a high-altitude bomber, but the guy has a desk. It's much more like bringing a laboratory out into the war time field. And there's a lot of interesting stuff about thinking about radar as a way to isolate yourself from the battlefield and manipulate things on screens.

One of the technicians who worked on these radars was a guy named-- well, what's the name-- Douglas Engelbart. Anybody know what he did? He invented the mouse.

And he'll tell you, during the war I worked on radar. And I started to deal with like moving things around as blips on screens using things to turn things around. And after the war, when I started to work at Stanford and user interface stuff, he was not an MIT guy, some of the ideas for interactive computing really came out of this idea of looking at a screen.

This is a famous image, one of the Rad Lab's sort of iconic images. Anybody know

what it is?

AUDIENCE: It's Cape Cod.

PROFESSOR: It's Cape Cod, right. So this here is just a map showing you where the airplane was. And there's a radar on there. The antenna spins around. And this is one of the first H2X images, plotting out the contours of the land there. And so you'll see this appear in another second in something I'll show you.

But this gives you the sense of, very, very different from blips on a screen. You're really able to sort of map where you. A whole other level of detail and in the military setting, that was very, very important. Here's even a higher resolution one. This is an image from an airplane, looking at another airplane nearby.

And just to get a sense for that resolution, too. You know, crude by today's standards in some sense of digital radars and stuff, but pretty fancy for that day.

And anybody know what this is, dead giveaway? This is the northern coast of France on D-Day. And here is the radar image of the fleet that's going to be the invasion force, taken from an airplane. And you can see 6 June, 7:00 o'clock in the morning, taken from a plane that was above. This is Western England.

Another interesting radar is this one. It's a SCR-584. It was actually the first tracking radar. And so in the history of control theory and feedback control, it was the first radar that could actually move its antenna based on where it's target was and follow something. And they actually used these to track the buzz bombs that came across to England later in the war and shoot them down.

It became also sort of an iconic radar, because this tracking head, it's interesting, it was made by Chrysler. And a lot of the gearing in it was taken out of Chrysler trucks. And it has these servos on it. It was a very, very good, very high precision tracking head.

You see it in post-war photographs for tracking rockets and doing sort of early NASA work. And you'll still see these radar mounts. If you ever watch like storm

trackers or anything, and their people who track tornadoes and stuff, they actually use army surplus radar mounts like this.

But this radar also, sort of serves the same purpose as the 268 that I showed you before. but again, they bring the operators inside the trailer, inside this sort of closed laboratory. And it's very much thinking of the battlefield and the electronic battlefield of bringing all these blips into a laboratory setting. And again, but the ultimate culmination of that are these big command and control centers you see during the Cold War, you see during the space program, but it's just the beginning of that.

That's the inside of a CR-584, where they can plot things on the map. Also, this was one of the early air traffic control radars. It was precise enough that they could tell the pilots where they were and guide them by radio, say come up, come down, come up and down, and land them in very, very rough weather conditions.

So I think this is the last image. This is actually an important image. At the end of the war, anybody know what happened to the Radiation Lab? Is it here today? Any of you students in the Rad Lab? Nope.

AUDIENCE: I think part of it became the RLE.

PROFESSOR: Part of it did become the RLE. And the rest of it? It just closed down one day. And went from 1945 to 1946, it shut down by a factor of 95%, and then all together in 1947. Which is a very interesting thing. It would be very hard to do in today's world.

Remember from the Hunter Dupree article about Bush, one of the reasons he was able to grow this thing so quickly and so rapidly was that he always promised it would only last until the war was over. And then it ended and he kept true to his word. And the OSRD closed down. The NDRC closed down. And the Rad Lab just closed down.

Which by the way, was not a bad way to influence the American electronics industry. Why?

AUDIENCE: Probably there were lots of people who knew about electronics looking for work.

PROFESSOR: It dispersed all that knowledge out into the world. And a lot of those people, many of them went to work on radar, but a lot of them went to work on television. The early American television industry was largely composed of Rad Lab graduates, who knew a lot about high frequency control.

Also a lot of the early vacuum tube computers, Eckert and Mauchly, who built ENIAC at University of Pennsylvania-- I know I'm going to forget which one-- I think it was Mauchly, came from the Rad Lab, where he learned about how to make vacuum tubes do high-speed pulse electronics, which by the way is essentially digital electronics.

So these people all dispersed into the world. The RLE, which still does exist today, became the kind of intellectual core, people like Wiesner and Wiener, a bunch of other people-- I'll talk about that in the next two weeks, I think. And otherwise, the Radiation Lab closed down.

But before they did, I meant to bring one of these, they published everything they did in a big series of textbooks. I think it's like 28 textbooks. And they just published it out to the world by McGraw Hill, not secret, not classified, none of that. And some of the first books in servomechanisms were there, antenna design, systems engineering. The first book ever in systems engineering came out of the Rad Lab. It was called *Radar System Engineering*.

And they have this characteristic. You can still get them. But the original ones had this sort of burgundy cover with it. And this was the logo they had on the front.

So what is that logo? It's the Cape Cod image. Anybody know what this is?

AUDIENCE: That's the cavity.

PROFESSOR: Yeah. That's the shape inside the cavity magnetron. It's sort of their logo. And if you cut a cavity magnetron open, that's what you'd see, is those little circles that are all the different resonate cavities, where I believe the wavelength of the radar is the

circumference of that cavity.

I meant to bring-- I have a few of the volumes. I don't have the whole set. You can buy the whole set on eBay. It's not hard to find. Because most people think of it as obsolete. But you can find them in the libraries, as well. And it's a very famous textbook series. And for most people who studied electronics in the postwar period, they learned a lot of it from this Radiation Lab series of textbooks.

So we were talking about secrecy and the effects of secrecy on campus. This is a sort of anti-secrecy effect, that it really just had the goal of-- yes, the Russians got it. Yes. Maybe some of our enemies learned something from it. But that was probably way less proportional than what our own people learn about it and what came out of it. I think that's my last slide.

AUDIENCE: That was the origins of OpenCourseWare?

PROFESSOR: The origins of OpenCourseWare, in some way, yeah. I mean I think that was the same kind of spirit. And that's one of the reasons that people like Bush felt that this stuff belong in universities.

Because if it was in the Navy lab or in an Army lab, it would go behind closed doors and stay there forever pretty much. It's very hard to get stuff published out of there. I'll just look at in the numbers I have here, if any of them--

So then going on from there, I mean the Research Lab of Electronics is a really interesting topic in and of itself. And they get into acoustics in a big way. People like, as we mentioned, Jerry Wiesner is there. Weiner is there. People like Amar Bose come out of there. And the Bose Corporation, who may make your headphones or your speakers, is a spin-off from the RLE.

Even people like Noam Chomsky kind of get their start in that world. And there are a lot of intellectual ties to, this is a little bit of a diversion, but if you think about some of the early work that goes on in linguistics here that Chomsky does, it has very much the same kind of systems engineering approach to it, about thinking about grammar and language, along the lines of people are thinking about these different kinds of

systems and systems ideas. That was the Lily Kay piece that Will mentioned, that we cut off the syllabus for this year. The same thing in biology, people thinking about information and communication in these more and more unified ways.

So what's remarkable about the war is that this effort ended at the end of the Second World War, but it had all of these kind of fingers that lasted. We'll talk next week about Whirlwind and digital computing and aerospace and stuff on campus. But it's not a coincidence the way that *Cybernetics* is published in 1948, Claude Shannon's information theory is published in 1948.

Also interestingly, I think it's 1948, Kurt Vonnegut first novel, *Player Piano*, is published in 1948. Has anybody read that book? It's a really interesting book.

And the lead character in it, I believe is named Norbert. Am I right about that? It's been a while. It's got a very clear allusion to Norbert Wiener. It's all about the implications of cybernetics in factories and other kinds of settings.

And there is this intellectual thread that runs through a lot of this work about this link between systems, and human machine interfaces, and communication, and feedback control, and computing, that you can carry that through at MIT. And we'll talk later about Project MAC, which is the 1960s. 20 years later, people are still thinking about interactive computing in very similar ways.

I mentioned Doug Engelbart, who was not an MIT guy, but very much is very clear in his memoirs, that he started thinking about these issues when he was interacting with the radar during the war. And then it's only out of this that you really get the beginnings of digital computing and I think, and I'll talk about this next time, a very particularly MIT take on those technologies that's not so much focused on the kind of basic mathematics of them, but really thinking of these computers as embedded in control systems, much in the way that all these different radars were embedded in control systems.

So that's where you can sort of see that the way that MIT is organized, the way that the federal government is funding science and technology, and the politics of

Washington around it, and the actual content of what kind of work people are doing, and what sort of ideas they're doing, are all really very much connected in this story about World War II. It's hard to overemphasize how much profound influence on the world that we live in, even just even just the local world here, came out of this really just five-year, seven-year period at MIT.

We also looked at "Science, The Endless Frontier." And that was where Truman came to Bush at the end of the war, pretty much at the end of the war, because Truman isn't even president until right before the war ends, and says, what are we going to do in this in the future? How are we going to take this forward?

And Bush writes this report, whereas somebody commented in the response for today, it's really very forward thinking where he says, OK, we're done with war. That's important. But let's really think about doing this in a context that's really going to help our people, and that's medicine and biomed and other sorts of civilian applications to it.

And that report to this day, I mean that's sort of-- has anybody read that before the class or heard about it? It's sort of basic required reading, if you have a career in science in the US. It really is considered the template for how the NIH and the NSF and a lot of other federal agencies work.

Interestingly, it's not so much the continuation of the OSRD model. The OSRD model kind of dies in 1945. If anything, it's carried on by the Office of Naval Research, which is a very small office, during the five years after the war. And then late in the '50s, I think it's picked up again when DARPA is formed in 1958, also with a very big MIT input. We'll talk about that next time.

But if you want to look at the modern heir to the OSRD, it's not the National Science Foundation. The National Science Foundation works by peer review. It has a charge to not only fund the best science, but to do education and to sort of spread its resources out, throughout the country in a kind of even way.

Whereas DARPA is much more based on the model of the OSRD, intentionally or

unintentionally. You have very strong program managers, who can sort of shape the fields the way they see fit. It's within the military, but it doesn't belong to the Air Force or the Army or the Navy. And it has does its own sort of thing. And it's sort of set apart, very much in the same way. But that's--

AUDIENCE: It's run academics.

PROFESSOR: --another story. It's run by academics, yeah. And the first director was Jack Ruina, who was a colleague of ours here. We'll talk about that next time. That's a post-Sputnik thing. That's the next big thing that happened.