WILLIAM BONVILLIAN: Let me just introduce myself. And then maybe you all can introduce yourselves to me and to each other. So I'm Bill Bonvillian. And for the last 11 years, I have been director of MIT's Washington DC office. And I've taught at Georgetown University a course on science and tech policy for about 12 years. And I teach a different course on energy technology policy at Johns Hopkins SAIS. So I'm on the edge on faculty at Georgetown and Hopkins SAIS.

And after 11 years of being director of the Washington office, I've stepped down from that job. So I'm now a lecturer up here. And I've got an attachment to MIT's Industrial Policy Center, which is one of its policy centers. And I'm finishing my third book actually, which is now at MIT press on advanced manufacturing. So you're going to hear more than your share about manufacturing for this all over. You're stuck with those realities.

And I had a background in-- I was in the executive branch as a child. And I was a Deputy Assistant Secretary of Transportation in my youth long before any of you were born and got to really engage in the development of major legislation that deregulated most of the big transportation sectors. So aviation, trucking, and railroads and then did a lot of work on surface transportation.

And then practiced law because I've been trained as a lawyer. So I practiced law for a decade. And then somebody I knew and had worked with at an earlier stage became US senator. So I get one of those proverbial Washington phone calls-- why don't you come up and we'll talk, Bill? And that conversation lasted for over 15 years. So I couldn't resist staying up there. It was much too interesting and fun.

So I had a long career working in the US senate and worked on lots of legislation but including a lot of work on innovation policy and science policy and R&D policy. So that's kind of where I got my training in this territory was very much learning by doing. And then 11 years ago, I went to MIT to run their Washington office, which has been a great joy. So anyway, that's kind of-- and then I, just as I said, just stepped down from that very activist kind of job to this life of leisurely MIT faculty. Supposedly, I'm quasi retired. I doubt it. But anyway, that's my background.

Let me just say a few things about how this course is going to work. We know from a lot of studies, that MIT's online crowd is now doing about learning science, that the talking head is not an efficient way to learn. So we really need you all participating in a class and coming into the discussion.

So to further that-- and you saw my email kind of introducing the course and you've seen the discussion in the syllabus. Those of you who haven't been able to get online yet, stick around after class and let's make sure you get registered and get access to the online materials and the background materials. So let's talk for a few minutes after class.

But essentially, we're going to use a discussion leader system. And what that means is that we'll all have five readings or so for each class. And I'm going to ask all of you to do those readings and then do a short-- doesn't need to be more than a page. It shouldn't really be more than a page and a half-- some key bullet points on the key findings that you drew from those readings and a couple of questions.

So that kind of gets all of you thinking about the readings on the way in and some cute questions you've got about the readings so that you can help own the class. Because it only works if you all own it.

And then, in turn, we'll do this discussion leader thing. So each week, I'll ask a couple of you to be leaders of the Q&A part of the class.

So here's how it will work. So I'll talk about any given reading for maybe 10 minutes, maybe a little more than that. And then I'm going to turn it over to the discussion leader to kind of bring you all into the review of the reading so that you get to participate in this and get your thoughts out on the table. And importantly, in terms of your learning process, your thinking, your learning, your speaking, all of those are key to the learning process.

One thing which we know from MIT's online classes and the learning science work that's been going with them, is that the human memory fades after more than 10 minutes of the talking head. I mean, it is just not rememberable. And it's very important to change settings after that. So we're going to change settings, and it's going to be you, and you all are going to kind of lead the next phase, and then we'll go to the next reading. After we've talked about the initial one for a while, we'll go to the next reading, and follow this pattern through.

And then I will always try to summarize, either at the beginning of the end of the class, where we are, because we also know that repetition is key to learning, too.

So just a few elementary points about learning science-- there really is, actually, some design here. The discussion leader stuff is going to be very informal. This is going to be very relaxed. I don't want you to be concerned about having to do fancy presentations. Just speak for a few minutes about some key things that you found about the particular reading, and then try and draw out your classmates. Now, you'll get their one-pagers, their reading summaries, in advance. They'll get you get you those the day in advance. I'll get a copy, too.

So I'm going to set up a rough discussion leader agenda for the first few classes, and then we'll formalize it for the whole class. But all of you will be discussion leaders, probably, at least a couple of times. But again, it's very relaxed, it's very informal. And we're just going to be sitting around the table, and I want you to kind of really work to bring your classmates into the talking.

So questions about this? Let me talk about where this class is going to go, so you get a sense of the pieces that lie ahead. So the first couple of classes are really introductory. And today's class, as those of you who were able to get to the site saw, is really about economic growth theory, so innovation growth theory. And that's foundational. In other words, what are the pillars on which studying innovation rests? Clearly, the economic justification is one of the absolute central and probably the critical one.

So what does innovation growth policy-- how does it think, how is it organized? And we're going to be reading two very famous growth economists and talking about that-- three, actually, and kind of trying to put together the basics of growth theory so that we understand that and can use that.

And the second class moves into kind of a second part of growth theory. And we could call this innovation systems. In other words, innovation occurs in a system, and you have to understand the elements in that system. So we're going to talk about that systems approach in next week's class.

And then I'll give you two kind of key tools to work with. In other words, based on the first couple of classes, you're going to be able to look at another country, at a state, at a region, and you're going to be able to see how you can evaluate that area's innovation system. What are the factors that you look for, what are the capabilities that you look for, how do you assess them, and then, in particular, at the end of next week's class, how do you look at them as a system? And then we'll take that framework and we're going to apply that framework and add pieces to it-- to the rest of the class.

So the next two classes are really about manufacturing. So just in case you got the idea that this is just policy esoterica, we're going to have a very real dive into some very real problems that are, frankly, at the heart of the political disruption that's going on now in the United States and elsewhere. So we're going to do two classes on that. So a deep, very practical, very real dive into a really important and very current innovation system problem.

And then we're going to go back and pick up some pieces we started with the first couple of classes. So we're going to look hard at the US innovation system, particularly the federal pieces of it-- the federal R&D agencies and organizations that are part of US innovation system.

AUDIENCE: What is R&D?

WILLIAM BONVILLIAN: Research and development. Don't hesitate to ask questions, by the way. Please bring those forward. So we'll look at the research and development system--

[TRYING TO PRONOUNCE STUDENT'S NAME]

AUDIENCE: You can call me Steph.

WILLIAM BONVILLIAN: Steph? That is easier, OK. Thanks, Steph.

And where did it come from, how does it think, how is it organized, what are its origins. Because we're at MIT, I'll give you a lot of insider MIT stuff. Because MIT historically was involved in a lot of this. So you'll collect some good MIT stories, I hope, particularly in that class. But you know, MIT greats like Vannevar Bush and Alfred Loomis will come up in that class. Then, in the sixth class, we're going to talk about the major policy focus in science and technology policy, which is called the valley of death-- how do you get from the research side over to later-stage development. And that's been the major policy emphasis in the US system. There's a big chasm there, a valley. Building the bridging mechanisms across has been a big policy preoccupation. So we'll dive into that literature.

And we will also look at the fact that the United States actually runs two innovation systems. So we run the innovation system. Probably most of you are familiar with places like NSF, the Office of Science at the Department of Energy, NIH. So that's the kind of civilian side, but then there's a whole defense innovation system that is organized very differently. Lily is nodding her head, because we spent time on this in the first class. So we'll talk about that system, too, and kind of how that works.

And then, up until class 7, we've been talking about innovation as though it has to do with institutions. But people innovate, not institutions. So innovation is owned by people. It occurs in a very face-to-face environment. You can't just understand innovation by understanding the institutions that are sticking their hands into it. In the end, it's a people system. And how do people-- what does innovation look like when people are running it at the face-to-face level? And it turns out there's literature on this. There are some rules that innovation groups tend to follow when they're undertaking their process of trying to get to a breakthrough. So we'll look at the organization of innovation systems at the face-to-face level as well as the institutional level. And that class, you all will own, because I'm going to have you all present-- a whole group of you-- on great innovation groups.

And then we've got the foundations of set, and we're going to start to look at particular segments. So we'll take a deep dive into DARPA, the Defense Advanced Research Agency, and its innovation model. So that'll be kind of a case study. We're going to take a close look at energy technology. And here, Martha will help us get through the class, because she'll know much more than me. And we're going to look very closely at the life science innovation system that, on the federal side, is led by the National Institutes of Health, and some of the big challenges in that system.

We're going to develop an idea of how do legacy sectors innovate. Because the computing revolution was brought about by a new frontier-- creating a new frontier territory and innovation. But most of the economy-- more than 80%-- is owned by these established sectors. And it's much harder to bring innovation into those sectors. So energy is like the poster child for that problem, and we'll take a real look at that.

And then, at the close of the class, we're going to do a couple of, I think, more fun and interesting out-of-the-blue categories. So we're going to look at the talent base, and science and technology education, and all the challenges embedded in developing a strong S&T talent base.

And then we're going to take a look at what we could call the future of work. So are you going to have any jobs? Are you going to be displaced by MIT-developed robotics? You aren't, don't worry. But that'll be one of the challenges that we're going to look at.

AUDIENCE: Is the future of work--

WILLIAM BONVILLIAN: Now, tell me your name so I get to know everybody.

AUDIENCE: [INAUDIBLE]

WILLIAM BONVILLIAN: OK, Martine.

AUDIENCE: So is the future of work based on Tom Malone's work at Sloan?

WILLIAM BONVILLIAN: We'll look at-- I tell you who we'll look at. We'll look at the kind of techno-dystopia movement, which Erik Brynjolfsson and Andrew McAfee at Sloan have been doing a lot of work on. And IT is going to replace a lot of work theory. We're going to look at David Autor, who's a wonderful MIT economist. And we'll read several things from David. But he's looking at all kinds of economic effects on job creation, including from manufacturing.

And we're going to look at some studies that try to take a deep dive into how much work is actually going to be displaced. And there's a fairly interesting new OECD study that came out this summer that indicates it's not going to be that bad. So we're going to look at all these kinds of issues, and kind of play them out. But I think it will be particularly interesting, and a kind of challenging session.

One more thing we'll do is, David Mindell, who teaches at STS, who is a wonderful technology historian but also a terrific engineer. So David is on leave from MIT this semester because he's doing his robotics startup. But he has a book called *Our Robots, Ourselves.* And he takes a really deep look. If robotics, in a way, is the most threatening entry to human work, what does that actually look like? What is actually going on? And he comes up with a thesis that's much more about assistive robotics and cobotics than about people displacement. So we'll look at all this stuff, and try and lay it out.

Anything so far-- questions so far?

AUDIENCE: Will we also be talking about economic competitiveness re international relations for example, manufacturing in China?

WILLIAM BONVILLIAN: Yeah. So we're going to do snapshots on international issues kind of throughout. So the basic focus will be in the US. But Matt, coming back to your question, there'll be a lot of underlying questions about how economic growth-- innovation-based growth works that's going to have a lot more applicability worldwide, including the developed and developing world. So you're going to get a toolset that will enable you to look at innovation much more broadly than just the US. You're going to pick up a lot of pieces about the US, but it's a much broader toolset than that, which I think you'll be able to apply. And we'll have a number of readings that will pull us into the international issues. What else?

AUDIENCE: Are you going to have any current events, especially during this [INAUDIBLE]?

[CHUCKLING]

WILLIAM BONVILLIAN: I'm always open to current events. When we talk about manufacturing, I'll try and give you a backdrop on some of that. So that's the third class. And you know, it's been a lot of social disruption in the US. And we'll try, through a reading by-- we'll talk about David Autor, and some of his work and findings in that area in particular.

And there'll be a lot of stories developing as the year goes on, I know. Anything else to start?

AUDIENCE: Yeah, question.

WILLIAM BONVILLIAN: Rasheed, right?

AUDIENCE: Yeah.

WILLIAM BONVILLIAN: Good.

AUDIENCE: So when we go through innovation systems, are we going to talk about methods or ways to kind of change and alter them, or are we just going to--

WILLIAM BONVILLIAN: You bet, you bet. None of this stuff is locked in stone. You know, I hope all of you will do startups at some point in your career. I hope all of you will be involved in innovation policy and issues. And part of the tool set you're going to get is how to think about those innovation systems and how to think about organizing them in an optimal way. If anything, that's the key thing I want to convey in this course, so that when you're running this country, you've got an agenda ready to go. Anything else?

All right, so I'm going to do more talking in this class. I'll do less talking in future classes. Hold me to that. But let me kind of summarize what we're going to see in today's class.

So we're going to talk about Robert Solow. And his contribution is to think about a critical factor in innovation, a direct innovation factor, which he refers to as technological and related innovation. So that's a term that I want you all to recall-- technological and related innovation. We're going to use that a lot, and we'll talk in a minute about what it means.

And then we're going to talk about another great growth economist, Paul Romer. He was in MIT for about a year, and then ran out. He's a character. And we'll talk about him, too. But he comes up with our second direct innovation factor, human capital engaged in research. And we'll talk about what that means.

And then, third, do these factors actually make sense? So Dale Jorgenson is a Harvard economics professor of note, another great growth economist. And he takes a deep dive into the IT revolution of the '90s and the period leading up to that, and he essentially concludes, yeah, this was technologically-driven, innovation-based growth. It drove a huge growth in the economy.

And then we'll have fun with a little study by Merrill Lynch, which is an investors' look at innovation, and how do investors think about investing in innovation. And then we'll look at some-- I asked you all to look at NSF indicators. I'll explain what that is in a bit. But we'll look at some ways of looking at those two basic innovation factors-- the technology R&D factor, the talent factor, and if you look at those, what do those look like in the US?

So part 1 here is the kind of fundamental factors of innovation. But let me get some general terms on the table. And I will post, by the way, the lectures, after, on the stellar website, so you all have access to them. But there's some terms that will recur here. And you don't need to memorize them now, but they'll be posted today or tomorrow.

So science-- science evolved as a way of understanding the natural world. It came out of natural philosophy. It's an 18th/19th century kind of conceptual framework. It is observational at heart. It observes the natural world, and attempts to understand how it's put together. And it's organized around discovery about that natural world and its order.

Technology is really different. It is a system to organize scientific and technical knowledge to go after a more practical purpose. And this systems includes the technical advance plus models to implement that advance. So you move from observation to implementation. And this is, obviously, the historical boundary between science and engineering.

And research-- another term we'll use constantly-- means increasing the scientific or technical knowledge or both. So research can pursue either of these historic ends, or both simultaneously. Invention is about applying research knowledge to create a practical idea or device. Invention is really different than innovation. Innovation is built on scientific discovery and on breakthrough invention or inventions, but it is the system of research invention development that uses both scientific background, scientific knowledge and technology knowledge to lead to the implementation and widespread applicability of a technology area. So typically, in our society, that means commercialization.

So this class is about this. That's the stage we're most focused on. But remember all the input above that that goes into this. Now, an innovation system-- we talked about this briefly before-- is the ecosystem for developing innovation. And as we discussed, briefly, it operates at least two levels. It operates at the institutional level of supporting the development of the inventions and discovery that go into innovation, but it also operates at the personal, face-to-face level. Because in the end, people-- you all-- innovate, not some fancy institution.

Innovation wave theory-- in economics, this is called Kondratiev theory. And we'll talk more about this as the class goes on. But let me just give kind of a snapshot of what I'm talking about. Innovation tends to come in a wave. And in your lifetime, the big wave has been the IT revolution. If we were born in 1800, railroads would be like a big innovation wave. Early telegraph-based communication would be a big innovation wave. Electricity would be a big innovation wave. And you tend to have a core technology advance, you pile on applications, and it begins to move through an entire society and affect the whole society. And to some extent, the technology drives the nature of the society. So that's what Karl Marx believed. That's called determinism, that the technology plays a deterministic role in the organization of society. So it's big. It is very big. It's not just a pile of new technology stuff, and it's fundamentally changing the way in which this society is organized as well. So that's also part of these innovation waves.

So a wave hits an economy, takes a long time to grow, eventually it scales up, and affects a good part of the economy at any given time. Eventually, you run out of the technology menu, and it stabilizes. But it doesn't disappear, it creates a new plateau in your economy. And then you do another wave. Yeah.

AUDIENCE: What do you mean by run out of the technology?

WILLIAM BONVILLIAN: Let me see if there's-- is there any chalk down at that end, Martha? I don't see any. It's all right. Oh, there is?

MARTHA: [INAUDIBLE]

WILLIAM BONVILLIAN: Great. We'll come back to this, but it's an important enough idea. So there's a slow build-up, and then there's a rapid build-up. Then there's a bubble. Then there's slower scaling. And then, eventually, you reach technological maturity-- sort of three scales. This is where the bubble is.

So the IT wave, right? Somebody-- I don't know where this starts. Maybe it starts with Babbage in the 19th century. But let's start it with the ENIAC computer at the end of World War II. 1945, 46, right? Slow scale up. Then you hit 1990s. And then you have very rapid scale up, right? And you probably had some sense for what that era was like. But it was a period of remarkably big growth rise, big increase in GDP growth rate, accompanied and driven by a big gain in productivity. We'll come back to that term in a bit, too.

Then there's always a bubble, right? So if you all are investing in innovation waves-- if you go into the financial sector, and you're investing in innovation waves, trying to ride them-- you want to start about here, ride it all the way up. But never forget that there's going to be a bubble. There is always a bubble. In every innovation wave so far, there's always been a bubble.

So in the IT revolution, that was the dot com bust of 2001, right? And then, we're in a long period of continued technological advance, but not at the rate of the 1990s growth period. And you can think about different generations of companies that come along and play different roles here.

And then, at someday-- and IT may be different-- but someday we'll reach a certain amount of technological maturity. And the growth rate will stabilize. And then we'll do something else, right?

So that's kind of what a wave looks like. And again, you build into your economy a series of mesas or plateaus, which don't disappear. You just go on to the next innovation wave. This is the way economies grow, through these innovation lives. So it's a pretty important concept.

And if you can get your technology advance into an innovation wave, then it kind of goes on autopilot, right? And all these things start to occur.

So that's what we're desperately trying to do for energy. We're trying to get it scaled up enough so that it can take off, go on autopilot, and just kind of happen.

AUDIENCE: So you mentioned there is a bubble present. [INAUDIBLE] wouldn't that affect [INAUDIBLE] this growth?

WILLIAM BONVILLIAN: Yeah. It wipes out lots of the dot com startups, right? They die. And only the stronger companies with more solid enduring models survive. So always anticipate the bubble. And get out in time. That's the key.

AUDIENCE: [INAUDIBLE] have a different perspective, they see it as two bumps. They see it as one baby bump, and then a huge bump So for the 90s, it was, like, it would cost you like $70,000 to buy servers. So those businesses took a lot of capital to start. And so people get really, really excited. And so they start to invest a lot of money. And then they expect the bubble.

And then, no one wants to invest. Because there is just a bubble. And then, people keep innovating in the technology until it's perfected. So an example of that is, like, once we had the mobile phone, in 2010, then you're going to have a lot of apps and have a lot of disruptive innovation.

So VCs usually just look at it as two bumps. But the second bump is usually just massive [INAUDIBLE].

WILLIAM BONVILLIAN: Well, and you can look at this as a couple of bumps, but not quite in the way, Martine, that you're describing. But you could look at this rise and then this phase. It's kind of two different pieces, too.

So that's another way of looking at this. Rapid growth, more stable growth, with different firms typically involved in the two. We're going to dig into this. But go ahead.

AUDIENCE: I was just going to ask, what are the key indicators that a bubble is--

WILLIAM BONVILLIAN: You're getting rich, right? A lot of people are getting rich, right? That's the key indicator. In the IT revolution, everybody got a lot better off. So all quintiles of the society ended up with a significant gain. You know, the upper middle class, as usual, gets the biggest gain. But everybody went up in that time period.

I'm stealing my own thunder from later in the class. But actually, we'll deal with some of this when we talk about Jorgenson. We'll get into productivity and GDP growth. So make me come back to this.

All right. So we got through innovation ways, more or less, with more to come. And then we talked earlier about this Valley of Death concept, right-- the gap between research and later stage development that has been the main focus of public policy in the innovation field.

One of the things about this class is that you're going to realize this is only one part of a much more complicated and richer story. So we're going to be telling a lot of stories in addition to this story. But that's one of the stories we're going to tell.

So any further questions about this? I just wanted to get some basic vocabulary kind of out on the table.

Let me say a few more introductory things. The relationship between science and technology-- really, before the mid-19th century, technology wasn't really based on science. It was based, in a way, on tinkering.

And that's not to say that science didn't enter at some critical stages. It does. But the initial invention moments are technology types fiddling around in the 19th century and late 18th century-- the equivalent of a garage, right?

So science is not far enough along to be able to give birth to technology, for at least a large part of the 19th century. But now we're in an era where basic science definitely can give rise to technology.

Now somebody-- a friend I know pretty well, named Lee Buchanan, who is a former deputy director of DARPA-- would always insist that, yeah, that's all fine. But I'm running DARPA. And I get nothing out of basic science. I could drop all that funding and never miss it, he explained to me one day.

So I think he's wrong. But you should know there's a debate about this, including in our most famous advanced technology agency.

But I think, in the end, the evidence is strong that science can now give rise to technology. But keep in mind that technology still gives rise to science. And we'll talk about what that means in a bit.

Now here's our first MIT great. Forgive the MIT-centric focus here, for our colleagues from other institutions. You'll have to bear with me.

Robert Solow won the Nobel Prize in economics in 1987 for, essentially, developing growth economics. I mean, he created an entire field of economics. And he's just a wonderful human being. He's still around. If you ever get a chance to meet him or listen to him, don't miss it. He's one of the greats.

Forget the Nobel Prize. The really important prize is the President's Medal of Technology, right? The only economist who's ever won the President's Medal of Technology. There he is getting it from Clinton. It's really unusual. His work is so important in its implications for technology development that he gets the technology prize, too, from the president.

I can't tell you what a nice person he is. I once watched him testify in front of the House Science Committee. And it was like, you know, God has entered the room. Solow has come into the room.

And the committee all knew that innovation based growth theory comes from this guy. And they were just incredibly complimentary. And the congresswoman who was, like, the number two or three on the committee-- so her questioning was fairly early-- and she turned to him and said, you know, doctor, you know, for the purpose of this hearing, you know, what should we call you, Nobleist? You know, what term should we use for you?

And he kind of leans back. And he says, well, you know, I was a tech sergeant in the army and during the Korean War. And I really came to like the title Sarge. So maybe you could call me Sarge.

[LAUGHTER]

And there's this fancy congressional committee calling Robert Solow, Sarge, for the rest of the hearing. He had them eating out of his hands. He was just funny and charming and incredibly thoughtful, all at the same time. So he's quite an amazing figure.

He wins the Nobel Prize for essentially blowing up a large part of classical economics. And the problem with classical economics-- and look, I asked you to read this. And it's his Nobel Prize talk. So for economics writing, it's fairly accessible. But even then, it's not simple.

If you're going to be reading it-- and I'm going to ask everybody who hasn't done the readings yet for this class, because I know it's your first time with access to the Stellar site-- but just blow by the economics formulation period. Just blow by the econometrics. Just get the basic ideas down for both Solow and for Romer, in particular. The Romer one is particularly complicated reading, for those of you who've not studied economics.

But he goes after classical economic theory. And just to summarize, in a simpler way than is really fair to classical economics, classical economics asked when an economy is capable of steady economic growth. And they never came up with a good answer.

The formulation was when the national savings rate, which means income saved in the economy, equals the capital supply, capital output ratio, and the rate of labor force growth, that's labor supply, then you get growth. That was the theory, all right?

So let me simplify that even more. Essentially, you've got two factors. Capital supply and labor supply. And it's not capital supply, like, all the money. It's capitals like plant equipment, as well as resources, that's available.

And labor supply includes not just the number of workers, but education health systems and the supporting systems for that, too. So these are bigger concepts. So essentially, their theory was that these are the contributing factors, capital supply and labor supply. And when you get those in the right balance, supported by your national saving rate, which is essentially the funder of those systems, then you will get economic growth.

It's a static view. It's an equilibrium system. And these factors have to be in the right balance-- they constantly tend to throw each other off-- for growth to occur.

So you explain a business cycle from this. I mean, not really. But that's what it attempts to do. And capitalism becomes just periods of alternating improvement and gain and decline. So it's a business cycle kind of explanation. Worsening unemployment and then labor shortages, right? Everything is throwing each other, over time, out of balance. It is not a dynamic model.

I should explain that classical economics basically starts with Adam Smith and lasts until, really, the post World War II period. And the problem with economics that was so frustrating to economists, as well as policymakers, was that it didn't really have a foundational set of operating and working assumptions that were reliable. It didn't have a reliable base.

So if you had 15 of you were economists sitting around trying to explain to me, a policymaker, how come there was a Great Depression, you would have at least 30 ideas on the table, right? It wasn't really terribly helpful to me. There were just too many variables.

So social science, in the course of World War II, saw what physics did-- staring at our two physics guys here. Well, there's more-- several physics books. Physics, in that pre World War II period, attempts to get down to basic known scientifically established currents of fact that can be demonstrated and known

So that's the whole particle physics endeavor, right? We're going to weed out extraneous stuff, get down to a fairly small subset of stuff that we really know, and then work with those as building blocks.

So all of the social sciences watch what happens to physics in that pre World War II period, and that World War II period, where eventually things like nuclear weapons and power come about. And they think, gee, maybe they're onto something. Maybe that's a practice that we ought to do. Can we get down to a relatively small number of known variables and, in effect, create a known system here that's much more reliable than the kind of pre World War II guesswork in economics-- that everybody would be working from a similar kind of problem set?

So that's the enterprise. Solow is a neoclassical economist. So he's post classical economics. He's part of a movement, which Paul Samuelson, here, is one of the tiny handful of the great leaders of that tries to get economics down to a subset of known factors and known realities that can be demonstrated and mathematically proven.

So that's what neoclassical economics is up against. That's what they're trying to do. Solow is a neoclassical economist. And he is working through this problem of growth. So he had, what, 150, 200 years worth of economics? And they didn't have a viable growth theory. I mean, what's with this?

So, fortunately, Solow comes along. And he forms one. And he said the story told by these classical models felt wrong. And he noted that in one of the classical economists, Harrod, there was a hint and generalizations about entrepreneurial behavior. And he decided that he could think about replacing the capital and labor output with a richer and more realistic representation of technology, which would be a new theory of production, not just an assessment of output levels.

That's the key thought pattern here. So it's not that capital supply and labor supply aren't important, right? They remain important factors. But they are not close to as important as this more realistic representation of technology, which he also calls, as I said earlier, technological and related innovation.

So it's not just the technology, right? It includes that bundle of stuff around the technology, like process and business models that enable it. But in the end, it's technology-based innovation that becomes the heart of economic growth. And Solow does a 50 year review of the US economy.

And he concludes that in that 50 year time period, technological and related innovation is the dominant causative factor of US economic growth to the tune of about 2/3.

So in that range, somewhere between 50% and higher. We may be on the higher end of that, now, in this era that we're in now. And that's his key breakthrough. So capital supply and labor supply are significant. But they're down in the teens.

Now he acknowledges that the rate of growth is going to depend upon the investment rate. Because that will be a factor that helps drives it. So capital supply here is still significant. But old growth theory, classical growth theory, is mechanical.

It is an equilibrium system. It's constantly going in and out of balance, hence those business cycles. The great thing about what Solow comes up with is that he brings a dynamic factor into understanding growth.

I'll skip some of this. This can be very good news, OK? So economics goes from like this kind of dark and dismal science to a way in which a society can grow and increase its well-being by introducing more technological and related innovation.

That's profoundly good news. It gets us out of this old equilibrium system, this old dismal science on to what, if you can get it going, what can be a dynamic pattern, and improve societal well-being.

We can see these technological innovations in the way they changed society in the past, right? So we think about what the 19th century looks like. And I mentioned some of these before. But you know, canals and railroads and electricity and the telegraph and the telephone, and more recent times, aerospace and computing and the internet, these are all growth transformers, right?

And you've seen a couple of these. You've seen the IT revolution in your lifetime. And you've seen, on a smaller scale, but still significant, biotech revolution, both of which are still playing out.

So you can get a feel for what these things look like. We kind of know they're real. This is not just some Solow construct. We feel these. Because we see them around us.

So what's the pattern? So there's a core technology advance. That yields opportunities for new applications which can pile on to that core technology advance. And then that, in turn, can become big enough that it enters society at scale, right? And we also the IT revolution spreading into different parts of the economy.

And then that can yield productivity gains. So productivity gains, for you non-economists, are when you're producing more with less labor input-- so more for less, right? Workers spend less time on the production stage. And they produce more, right?

So those are the efficiencies that come out of technology, enable these productivity gains. The productivity gains-- that is a real gain in this society. That creates real wealth. Because you're producing more with less. So there's a real gain.

And then, depending on how your society is organized, you can distribute that wealth. And the society can move ahead. So that's what we saw happening in that amazing 1990s period, right? And we'll talk about Jorgensen and the pictures of that, in a minute. Follow me? Are you with me?

So, great. We're out of dismal science. There's really good news here. You can do this innovation stuff, and grow your society, grow your economy, and grow societal well-being, right? That's the good news.

The bad news is how the heck do you do that? How do you do that? And that's what this course is about-- how do you do that?

For a long time, economists thought that this technological and related innovation stuff was the way in which rich nations got much richer. And that's pretty much the way it looked, for a long period of time.

But then, funny things started happening, right? Countries like Korea, Taiwan. But then, really importantly, India and China hit on aspects of a technological based innovation model and began to significantly grow the middle classes in their societies.

So we now know this is not only-- Matt, this is for you-- this is not only a model for developed countries, this is a developing country model, too. This is really important, right?

So technological progress is key. Capital is a supporting role, but still important, right? Labor supply is a supporting role, but still important.

And Solow brings us this whole new set of ideas. But then he runs into a problem. Because remember, he's a neoclassical economist. He wants to get down to a small number of variables that you really know, right?

Good luck with trying to understand an innovation system based upon mathematically proven small numbers of variables. It is much too rich and complex a system. You can't put an innovation system into supply and demand curves.

So Solow sees the power of technological advance. But he doesn't see how to measure it. So he can't put it into his neoclassical economic model. So he treats technological innovation as Exogenous-- outside of the economic analytical modeling process that he's involved in.

That's pretty amazing, when you think about it. This guy figures out the dominant causative factor of growth, which is, needless to say, a pretty important thing in economics. And then he can't play with it, right? Because it's outside his system.

So that brings us to this character. And this is Paul Romer. And you can see, you know, very California, right? And he's got that laid-back kind of relaxed look in his eyes. And he is a remarkable figure. He is a maverick troublemaker, all right?

You know, I got to know him by actually working on some legislation with him, back when I was working in the Senate. And we knew we needed to improve the STEM, education science and technology, work base that was going to be pretty important for reasons I'll explain in a minute.

And how would you do that, right? So I'm a senate staffer. I'm thinking, gee, we're already spending, you know, X billions of dollars on fellowships for you guys. And we're going to have to find billions more and increase the number and expand the base. And it's going to be incredibly costly. And I'll never get this passed.

So Romer is thinking about all this stuff and writing about it. And we'll read something else of his late in the class. But I sat down with him. And he said, Bill, you're not thinking about this right. He said, think like an economist.

He said, you don't have to subsidize everything. You just bribe the gatekeepers. That was his phrase. And his point was, you don't have to throw a huge amount of money and build up all kinds of programmatic elements. You just figure out who's not doing their job, and expanding the number of scientists and engineers studying at universities. And you bribe them to change their ways. That's the way you do it, all right?

Much cheaper. And sure enough, we fashion legislation and eventually get it passed. I'm not sure it changed all that much. But it was a fun exercise working with him. Because he definitely has this maverick troublemaking perspective.

At one point in his career at Stanford, he realizes the incredible inefficiency of economics education, that his students just aren't getting the big ideas by listening to lectures and reading textbooks. It's just not happening.

So he walks out of Stanford, and sets up his own economics textbook company, which is anti textbook, right, and essentially develops a whole set of modules of learning by doing exercises and problem sets and online elements.

And so you don't get a textbook, yeah. You get something with a textbook. But you get all kinds of online pieces that you do constantly in getting through this.

So he completely blew up the whole economics textbook industry and has forced an absolute fundamental reform. And then he went out and proved, yes, my new system here works better than Paul Samuelson's and everybody else's textbooks. Because people are absorbing the core ideas and be able to work with it much more efficiently.

It's a whole learning by doing problem based learning set that he brings in to economics. So you know, he just walks out of his economics job at Stanford and does this for four years. And now he's on the latest of his exercises, which is, he went to NYU a few years ago to work on sort of cluster development theory in cities and metropolitan areas and growth.

But then he left that. So he's now chief economist for the World Bank. And look out, right? Because there's going to be trouble ahead here. He's going to change that place, I'm confident. But let's talk about the ideas that he brings to our problem.

AUDIENCE: When did he switch over, Bill? [INAUDIBLE]?

WILLIAM BONVILLIAN: This past summer. I think that's when he started. I haven't seen him since he started. But sure enough, one thing he does, he writes this attack on economists saying they're completely in love with, you know, metrics and mathematics. And it's not going to get them anywhere. These systems are too complex.

And it's just an assault on the profession. Because this is a profession, like all professions. It doesn't attack itself, right? It's not polite, right? So Romer just lifts the veil of trouble.

It's quite a piece. It hasn't formally been published. I'm not sure any journal dares publish it. But it's definitely circulating around. I'll try and find it for you. Because it's a fun read. It's really something.

Anyway, that's Romer. And Romer is on this project. His famous 1990 piece-- which, frankly, probably should win him the Nobel Prize in economics, but he's such a troublemaker that it probably won't-- is called Endogenous technological change.

So he's trying to reverse Solow's exaggerate exogenous change and make it go back, get these ideas of economic growth back into an economics thinking framework. That's his project here, right? And he starts on this pathway.

I mean, let me just summarize the basic points. He agrees with Solow that growth is driven by technological change. And then he argues that that in turn is driven by researchers, who he describes as economic agents, profit maximizing agents.

And then he looks at how technology isn't really a conventional good, in the normal sense of economic goods, but has its own set of unique properties that make it really quite different. But most important for us, he looks at what he calls Human Capital Engaged in Research.

In other words, you don't just have to do R&D to loosely summarize Solow. You've got to have a talent base doing that R&D.

This whole project is to take all these concepts and move them into an endogenous theory of growth. So his growth model is similar to Solow's. He's picking up on Solow's work.

He sees that technological change is the heart of economic growth, as we've discussed. He sees that technological change occurs, in turn, in a large part because of people responding to market incentives. Again, he's trying to get this into economic thinking.

And this technological knowledge, which is instructions for working with materials, is inherently different from other economic models. So developing a new and better set of instructions, he argues can be treated as a fixed cost in economic terms. And it's, therefore, a defining economics characteristic of integration.

So just for an example-- and this article is richer than this. But I'll just cite a few examples of what he's trying to think about. A Rival Good is property that, if used by one person or firm, precludes use by another. And a Non-rival Good is a kind of property that, if used by one person or firm, in no way limits the use by the others.

So technology, he argues, is naturally non-rival, right? Because it can be readily shared and adopted by others.

In other words, once you see this thing and understand how it works, then you can make your own version of it, right? But there's obviously-- how would you get rich off this if it's completely non-rival? So capitalists move to make it excludable, right, where the owner of the good-- Steve Jobs and his crew-- try to prevent others from using it, for example, through trade secrets or patents, right?

So technology can be made partially excludable. But in the end, technology has these, remember this term, spillover features-- knowledge spillover features-- that make it pretty accessible. Because you get to see the technology. And you can derive ideas about how it's put together.

So technology is unlike any other kind of economic good. Because it can be both excludable and non-excludable, rival and non rival, right? It's not like anything else. It's not like owning a farm, right?

AUDIENCE: [INAUDIBLE]

WILLIAM BONVILLIAN: And you are?

AUDIENCE: Max.

WILLIAM BONVILLIAN: Max, good.

AUDIENCE: This is saying that technology just really specific technology or technology in general?

WILLIAM BONVILLIAN: Technology, in general. So he's developing a broader way of looking at this whole category. All right.

So that's one core idea. Let's try and develop theories of economics by which we can better describe what technology is, since it's so key to growth. But his really important contribution is around the role of human capital. And that's what I want you to really remember today.

How can I explain this? So it's Rome-- whatever it is-- 200, right? It's Rome. And Romans, they're terrific engineers. They figured out these amazing roads. And they stuck them around all over Europe. And that's a technology advance. And it improves communication systems and transport. So it's a technological advance that carries with it some gain.

Now the width of the Roman road is the defining characteristic of the width of railroads, right? That's the distance between the rails is defined by the Roman road distances, interestingly, enough.

The Romans had a very primitive kind of toy steam engine that Roman kids would play with. And it had an axle and had this little-- you heat it up with a candle or something. And then this little thing would spin around, puffing away. Because you know, water would boil, and so forth. And it would sort of spin around.

Romer would say that the reason why Romans didn't take the step of putting rails on their roads and sticking the steam engines on the rails was that they did not have enough human capital engaged in research. In other words, they didn't have a big enough group of people that were talented and well-educated that were figuring out how to move this toy steam system to an actual technology advance, moving through the invention and innovation stages.

So the human capital engaged in research was the critical determinant factor about why they didn't put these pieces together, all right? So it's not just doing a bunch of research. You've got to have the talent base doing that research, and that that will be a determining factor in whether or not you're going to get to the stage of technological advance.

So you follow me? So again, that phrase is Human Capital Engaged in Research. If you lack human capital engaged in research, you get economic stagnation.

All right. Let's do another picture. Medieval Europe. Let's face it. There's no human capital engaged in research-- maybe a few alchemists poking around in dungeons, all right? That's it.

So is their economic growth in medieval Europe? Not really, right? I mean, they learned something about castle building. But a lot of it came from the Romans, anyway.

Economic growth basically consisted of, you know, hiring a motorcycle gang and putting on our horses and riding over to the next guy's castle and looting the place. That's how you got gain, right? That was the economic growth model. It was stealing, right? It was like piracy, right?

There was no economic growth model. So it's not until the Industrial Revolution that you get a significant amount of human capital engaged in research that's going to be able to nurture these technology advances.

So we have our second innovation factor now. The first factor-- Solow. And again, I'm summarizing here. You got to do R&D. Technological and related innovation, you got to do some R&D.

Romer, the second factor, human capital engaged in research-- kind of the talent base. Behind that R&D system, behind that technological advance is going to be the talent base.

So that gives us two factors. And you guys can now look at any country or society or region. And you can now say, oh, I can start to look at that. I can look at, hey, are they doing a bunch of R&D? And two, what's their talent base like, right?

Romer developed something that he calls Prospector Theory. Now that's not in this reading. It's in some of his somewhat later work. But it's an intriguing idea. And it's very simple and straightforward. But it'll help you in making these assessments. So Romer looks at the chemical engineering industry in Europe in the late 1800s.

And he notices that there are two countries that dominate these early chemical industries, Germany and Britain. They have the big emerging chemical industries. And other countries are doing stuff in this area. But they don't have anything like what Germany and Britain are up to.

So then he looks behind those industries and finds that both Germany and Britain have very strong education systems for chemical engineers. So they are creating a talent base that enables the advances that they are making in chemical engineering.

So the idea is you've got a field of prospectors. So let's take it back to the origin of the idea. So it's the California Gold Rush. And it's 1848. It's not 1849, yet. It's 1848.

And you've got five or six people hanging around the Sacramento River, occasionally sticking a pan into the river. All right. Then a year later, 1849, you've got 250,000 people sticking pans into the Sacramento River and every traceable, you know, part of that river system, up every creek.

What do you think? You find more gold with 250,000 people? You bet. A staggering amount of gold gets found. That's Prospector Theory. And it's a little more sophisticated than that. But you're going to find more gold if you've got more prospectors on the problem.

Now you have to train those prospectors. It can't be totally amateur hour. It's much better if you have trained sophisticated prospectors, like Britain and Germany did, with the chemical engineering sector.

So you need that human capital engaged in the research system. If the human capital is driving cabs, it doesn't do you any good. You've got to have that human capital engaged in that system of research.

So you can then, now, make a further extrapolation on what Romer's thinking about, right? You have a way, now, of looking at fundamental strengths of an innovation system. It's an R&D system and the talent in that system. Questions.

AUDIENCE: To what extent does his theories include questions of inclusion?

WILLIAM BONVILLIAN: Really good and timely point. So if Romer is right and you want a large number of well-trained prospectors, and you're fencing off significant parts of your society from that prospector pool, you're doing something really stupid, right? It's just fundamental as that. That's how simple and straightforward prospector theory is.

That's why what's been happening over the last few weeks makes me so nervous. Because the US developed an innovation system that worked on encouraging talent from everywhere to come here. And it's a huge innovation advantage. It's huge.

In other words, if you're running an innovation system and sucking in talent from everywhere to help field it, to help staff it, that's really interesting compared to running an innovation system where you put fences around your borders. Not very smart. That's why 400 tech companies that joined the amicus brief in the case that's being argued today. Because they understand this. So there is a huge inclusion piece to this fundamental idea. Rasheed.

AUDIENCE: Is there too many cooks in the kitchen, upper bound?

WILLIAM BONVILLIAN: Yeah. I don't think we're there yet. It's always an important question. Does a society have too much innovation going on, right? And I think we're not remotely close to that. I don't think we're close to that, right?

In other words, if technological and related innovation is the key driver for growth, and we've got 2% growth at the moment, maybe improving the innovation system might be a way to improve our growth rate. Therefore, one way of looking at that is to get more prospectors on the problem, right?

So I mean, that's a simple-minded idea. But the prospector theory is pretty straightforward.

AUDIENCE: Out of curiosity, what would it look like, suppose we did have too many like he was saying, too many cooks [INAUDIBLE]

WILLIAM BONVILLIAN: I think we're just so far away from this that it's not really worthy of thought. I mean, look. Periodically, in the science community there's panic about, heavens, we've trained too many physicists, right? They're only going to be able to drive cabs, right? That we're in an oversupply situation.

And every once in a while, you get cycles that, frankly, largely resemble the business cycles that tell us that we may be at those stages. And panic hits the science community that we're training too many numbers.

But if we go back and think about what we've been learning here, which is that technological and related innovation is a dynamic factor in your society and your economy, it is core to the way in which you grow, then the talent base is a dynamic factor, too.

And you don't want to restrict the dynamic factor. Because you're going to limit your dynamism, all right? Don't shut down dynamic factors. Led them thrive.

The problem science has, it's not able to extrapolate to a larger use of its talent base, right? Just because there may not be enough jobs in formal academia for all of the scientists who are training doesn't mean that there aren't really important functions and roles they can play elsewhere, right?

So 2/3 of US scientists and engineers are employed by manufacturing industries, right? That's where actually most of the jobs are, not in the academy. And yet the scientific community views it as, oh, it's the academy. And that's where the oversupply problem is.

But maybe the key here is equipping that talent base with a whole new set of tools that enable them to play a broader role than simply supporting the academy, right? Maybe that would be a smarter talent based training idea.

Maybe you give them entrepreneurship classes, so they can think about starting their own startups. Maybe they get business minors, so they can do startup stuff. Maybe they get other kinds of training that gives them additional skill sets in addition to kind of classical research skill sets.

I think that would probably be a better answer than attempting to restrict the supply. The historical US growth rate is 3%. That's starting to look pretty good. Because we haven't been there for quite some time. It makes a big difference.

You all probably don't remember this too well. But the dynamic quality and feel of the US economy in the 1990s was very different. The sense of opportunity that was there was very powerful. And it was pretty pervasive throughout society.

And if technological and related innovation drives growth, and it's key to a higher growth rate, than the task is, not how do you shut that down, but how do you get back to a higher level growth rate, I'd argue.

AUDIENCE: My concern would just be, like, not too many cooks in the kitchen, but too many empty kitchens. Because debatably, the most problems today are energy, water, [INAUDIBLE]. But most people right now, 60% of the people studying at MIT study computer science. I'm pretty sure, like, energy, nuclear [INAUDIBLE] It's just like, you know, there's a lot of empty kitchens that are the most important problems. But also, from the capitalist perspective, it's like, you want a monopoly.

So it's the place you want to be. If you discover fusion, [INAUDIBLE] $38 trillion dollar market for energy. Most likely it wouldn't capture the whole market. It's too hard. So you want to go the path of least resistance. But ideally, they get like $10 trillion, $2 trillion [INAUDIBLE] So and the next trillion will probably be, like, space money or something like that.

WILLIAM BONVILLIAN: Yeah. I mean, that's an interesting idea, right? And I do think that we do have too many empty kitchens, at this point, that need staffing up, frankly. They need a path to growth.

And getting to fourth generation nuclear power, I mean, that's an absolute core climate strategy, in my view. But I think it's increasingly widespread at MIT, right? And we're not staffing that revolution up. In Romer's terms, we're not putting enough prospectors on the problem.

It's increasingly hard to organize startups to do something other than software and biotech. Because venture capital is just doing too well with those models. And look there's nothing wrong with software and biotech. it's important stuff. So there's nothing wrong with what we're doing.

But we are not funding other technology sectors. So we don't have a broad based approach on technology advance. See your metaphor, Martine, of some empty kitchens-- we're emptying our kitchens on quote, "hard technologies," where you have to manufacture something. Because the scale up process is much harder for that financing system to muster than scaling up a software startup where its infrastructure is in the cloud and doesn't cost anything, and can scale up very quickly with very limited amounts of capital.

It's much more complicated to stand up and do energy technology. It's a longer term project. And it's a more expensive scale a process. So we're not doing those. So we've got GAP. And we'll talk about this in the next class, In the innovation system. It's yielding a bunch of empty kitchens around our economy, whereas I'd argue what we want to do is fill those kitchens up but they've got to have a pathway to success as part of that. [INAUDIBLE], you follow me? Does that add up? Is that what you're after?

AUDIENCE: Yeah.

WILLIAM BONVILLIAN: OK.

AUDIENCE: [INAUDIBLE]

WILLIAM BONVILLIAN: Tara, right?

AUDIENCE: Tara, yeah. I feel like it kind of plays into this innovation wave idea, where people sort of flock and leave different kitchens to go to the one kitchen. And then, while there's all these empty kitchens [INAUDIBLE].

WILLIAM BONVILLIAN: Right. And, look. If we could get energy onto the wave, it would make all the difference. We could do it, all right? So if we could manage to get it into this phase-- and we're not, we're still in the build up phase-- but if he could get here, that's gets to be really interesting.

AUDIENCE: You mentioned that first phase is, like, between 40 and 50 years . At least for fusion, it's been like [INAUDIBLE].

WILLIAM BONVILLIAN: Yeah, Max. I follow fusion a lot. Because MIT has been so involved in this. So that's been one of my more fun adventures in recent years is working with your fusion team on some of these issues.

But you're right. The technological advances that could actually scale this thing, actually now, I think, for the first time, appear in sight, become plausible. Still a long term project. But I think we're a lot closer than we were a decade ago.

AUDIENCE: [INAUDIBLE] is because I took your science policy bootcamp, not this IP, but the previous one. And I was disappointed in the lack of consideration for cultural values in promoting R&D in science and technology. And I've had some conversations like this. And I'm always sort of prone to think about the values that we promote as a society, both in the United States and across the world, in the societies that they propagate, and how those impact, I guess, the projects that are funded are not [INAUDIBLE] in basic theories of development, for instance development.

There's a limited number of resources that any organization can apply to, if they're public, private, etc. And what we, as a society, value and how we brand that value and make it appealing and interesting to the regular consumer is of great concern to me, especially, because science is not something that's accessible or exciting to most people.

WILLIAM BONVILLIAN: Yeah. [INAUDIBLE], you're right on a whole series of big important problems that we need to keep bringing into this class discussion. And creating a culture around science and creating culture around technology and development, a culture around entrepreneurship, and a culture around startups, those turn out to be fairly key.

It's hard for economics that's trying to do mathematical modeling to capture these cultural, historical issues. But they're there. And you know, part of what makes innovation systems theory so interesting is just the sheer complexity of that system and the number of variables operating there.

And you're right on an important point. Understanding the historical context, for example, turns out to be pretty key when you look at innovation systems in different regions of the world, right? Different regions have different ways of organizing innovation systems.

The innovation system that got organized in Japan, coming out of the Second World War is a very different innovation system than the US organized. And we'll try and talk about some of that, actually, in the next class. But keep bringing us back to these cultural factors. Thank you. Martha, you've got a question.

AUDIENCE: I'm just going to briefly say... It's not really a question but politics and leadership really plays a big role here. And why haven't wenot to dwell on energy too much been able to pull up a Manhattan Project for energy or the [INAUDIBLE] getting somebody to the moon. I mean, those were clearly having the leader of the free world stand up and say, this is a priority.

WILLIAM BONVILLIAN: It would have been useful, right?

AUDIENCE: [INAUDIBLE]

WILLIAM BONVILLIAN: Right. And I mean, in a society, there in the end, there is no substitute for leadership, right? You really need a big dose of that as well.

And we will talk more about innovation systems and how can you nurture change agents, particularly, for innovation in these legacy established complex sectors, like energy, helping you introduce change agents. And what tool sets can they use to actually drive change.

So we'll talk about that, particularly, in the energy class. But it's relevant to many others.