

0:01

ED BLUCHER: Okay, good morning everyone. Let's get started.

0:05

So good morning. I'm Ed Blucher. I'm the director of the Enrico Fermi Institute that has hosted these Compton Lectures since 1976. Can you hear me? Ah, now it's working, okay, but you, I think you heard what I said. So we, we've been hosting these lectures since 1976. The coming year will be, will be 50 years. And I think all of you know there's a series of eight lectures in the fall and in the spring quarter. So thanks-thanks to all of you for being here. Thank you for your support of these lectures. Thanks to the Friends of Compton. So the topic of this lecture, as you can see on the screen, is the introduction to climate systems engineering. So these, these lectures, are unusual in a couple of different ways. One is, I think the topic is unusually interesting,

0:54

important, you know, and currently topical. The other is that these lectures, instead of being given by a new researcher, will be given by a group of faculty at the university that are part of the university's Climate Systems Engineering initiative, and they are people who are really world experts in the topics that you'll be hearing about.

1:14

So today's lecture is going to be given by Professor David Keith. He's a professor in the geophysical sciences department. He has worked for about 35 years at the interface between climate systems, energy technology and public policy, and I think all of those you'll hear throughout these lectures. I won't go through all of his accomplishments, but he led the development of the solar geoengineering program, a research program at Harvard, before moving to Chicago in 2023 as the founding director of this Climate Systems Engineering initiative.

1:49

So I think that's, that's what I wanted to say. So first, you know, thank you to David for doing these lectures. I think this is going to be incredibly interesting. And I'm, I'm looking forward to all the things that we're going to hear, and David will tell you about the other faculty members who will be speaking for the rest of the series.

2:08

DAVID KEITH: Welcome. It's a pleasure to be here. I'm looking forward to this. I'm going to start by telling you about this series and who will be speaking, and then by induction, hopefully you'll get some idea of what the heck this climate systems engineering is. And I should warn you, just to keep you thinking that there will be two quizzes here, so I'm going to be asking for your opinions, and I want you to really think about the right answer as if you were betting for money. So--so I'll just start with who's going to be doing the lectures.

2:41

So first of all, not in any particular order, but B. B. Cael is a relatively new faculty, the first of the new faculty hires associated with this Climate Systems Engineering initiative that I'll tell you about in due course. And he, I guess he started as an oceanographer, core expertise there, but has now broadly been doing exciting work across kind of interdisciplinary climate science. Second is Tiffany Shaw, again from the geophysical sciences department, one of the people really at the forefront of understanding the climate predictions and understanding the gaps and uncertainties in what we're seeing, that how we're seeing the climate change compared to what the models and the physics say about how the climate should change. Then me, who you just got an introduction to, and then David Archer, who's also from the geophysical sciences department, one of the real greats in understanding the carbon cycle, the interaction of the carbon cycle and the oceans and the long term fate and consequences of putting carbon dioxide into the atmosphere. And then Doug MacAyeal, recently emeritus in our department, super active in this topic, a glaciologist who's done extensive work in Antarctica, and who's become really interested in this question of whether humans could intervene to slow down or stop the melt of some of the big glaciers.

4:02

Now I'll kind of tell you about how we'll put these lectures together. There's, there's more methods to this madness, but it's also partly there because of different people's schedules. So, first lecture is this one. An introduction where I'm going to try to explain to you, if you want to take one thing away from this, the idea that the solutions base for climate has four dimensions. That there are fundamentally four categories of things, physical things, humans can do to reduce the risk of climate change. I want to convince you that four is the right number by the end of this lecture. And I'll give you some,

therefore some context, and some context of things we're thinking of as climate systems engineering. Not spoiling it too much, there's two main parts we're talking about: carbon removal, the idea that you can remove the carbon that we've put in the atmosphere back into stable storage; and sunlight reflection, the idea that we could reflect sunlight to reduce some of the impacts of the carbon dioxide in the atmosphere.

5:03

So the next lecture will be David Archer giving the kind of prequel, the underlying knowledge you need to understand the carbon cycle and how humans might intervene in the carbon cycle to reduce or to take CO₂ out of the atmosphere then, and that's partly because of holidays, otherwise we would have done it differently. Then Tiffany Shaw, Professor Shaw giving a kind of introductory lecture about climate science, which obviously underlies all of this, particularly focused on trying to understand the uncertainties and the physical basis for predicting the science response to CO₂ and to aerosols, which turns out to be important in its own right, and particularly important when you think about how humans might deliberately alter the system, because the main way we would do that is by adding aerosols.

5:51

Then the second of the two carbon removal lectures. So this is Cael's lecture, and Cael and David Archer work together closely on this, really applying all the science to talk about how specifically we might actually remove carbon, what some of the risks are, what the limits are, what the costs are, kind of where the scientific frontier is of that topic. Then me, in a sense, picking up on Tiffany's lecture talking about how we might deliberately reflect some sunlight to reduce the climate change from accumulated carbon dioxide. And in that first lecture, really talking about all the means by which humans might engineer sunlight reflection, might actually do it, but not saying much about what the consequences are or what the risks are. Then a lecture that's kind of going to be split with Doug MacAyeal and me. Doug MacAyeal giving this lecture on how the big ice sheets are melting, what's the physics of that melting, and how humans might intervene to reduce the mass loss from the big glaciers, which is going to cause sea level rise. And then me talking kind of separately about some work I did in the commercial world. I started a company called Carbon Engineering that does capture CO₂ from the atmosphere. I'm going to tell you a little bit of that story, not for the purpose of promoting or slagging that company, but as a way to draw some lessons about the both possibilities and some of the real limitations of the development of these new

7:19

clean tech or climate tech technologies I preview. I'm really excited about the work my and many other companies have done, but I think there are really interesting limits to what these companies can usefully do in this space, and I want to point to some ways that maybe things could be different.

7:35

Then, November 15th is Tiffany Shaw and me talking together about what the consequences of these sunlight reflection methods are, what the uncertainty is, how experiments might reduce those uncertainties, and a little bit about the policy associate with these things. And then finally, last lecture, again Professor Shaw and myself now talking really about what our vision is for the future of this climate systems engineering idea, field of inquiry, whatever you want to call it. So that's a kind of summary of how we're going to do it. And again, I haven't really quite told you yet what climate systems engineering is. We're going to kind of get there inductively, but this should give you some sense of what's coming. Quick question. Sure.

8:20

AUDIENCE MEMBER: I don't see up there. Does any of these talks talk about the melting permafrost?

8:28

KEITH: There will be a little bit in there. I would guess that David Archer will touch that a little bit. It's a fair question.

8:35

So now you got to start getting ready for the first quiz. So I've got two plots here. I'm gonna spend a while on this. So the top one is observed data, and we could spend a lot of time saying exactly what observations mean. I think it's right to think of these as modservations. They're combinations of observations and data. But these are really well thought out, from 1880 till 2020, this is the global average surface temperature. It's not actually the temperature of the surface, it's the temperature two and a half meters

above the surface. It's what we call the surface temperature. So this, you know, basically you can see that it kind of bounced around here, especially after the war it really starts to go off like a rocket, warming up pretty fast, and then on almost the same axes you can see, again, from 1880 but this time running right to 2023 you can see a time series of the emissions of carbon dioxide in gigatons or billions of tons of CO₂. This is carbon dioxide emissions from human industrial activity, which is basically fossil fuels plus cement. Those are the major things that make industrial fossil carbon, that move carbon from the Geosphere, where it's been stable for, in some cases, millions or hundreds of millions of years, move it to the active biosphere.

9:47

So this gives you a look at how carbon emissions have been going up and up. And, you know, no big news flash, these two are related. There's ways, in, no question, that the carbon emissions are in some way driving a significant portion of that temperature rise. That's a fact. So now I want you to think a little bit about what might happen next. So I'm going to extend the axes out to 2100 which is both far away, but also, you know, there are younger people in this room might live to see it. Certainly some of our kids and grandkids will live to see it. It's not infinitely far away. So extend this out to 2100. And now I'm going to imagine that we're going to cut emissions quite quickly. Suppose that emissions are cut to zero by 2050. For right now, don't think about how likely that is or how possible that is. I actually am prepared to argue that it is absolutely possible. Clearly it's possible we could just like, end civilization. But I actually want to make a stronger argument that it's possible to do that and still keep the lights running and keep industrial civilization going. I'm actually quite optimistic in some ways about emissions cuts. Obviously, that exact straight line is not a prediction of what's going to happen. But if we followed that straight line, if we brought emissions from what they are now back down to 2050 and then held them at zero, the question is, what would it do to temperatures? That is, what happens to temperatures in 2100 under a scenario where I've held--where emissions have done what I just showed? So you can imagine a big range of outcomes. Obviously, it's a continuous distribution, but I'm just like choosing five possibilities. I just sketched this up. I'm not giving you a real model. I'm going to label them A, B, C, D, E, and so what I want you to start thinking about is which one you think is most likely. So you're not allowed to go consulting the Internet. If you're right here right now, and you actually have to make a bet that you know your your grandkids will cash in on depending on what the right answer is--and obviously we don't know, because we're not going to run exactly these emissions trajectories--which do you think is likely to happen? So think about it. Choose one. I really am insisting that you choose one of them. It can be whatever you like.

11:57

Now what I'm going to ask you is, pretty quickly, one of the things that UChicago is famous for is thoughtful social psychology. So it turns out, if I just ask you to show your hands, you're all going to be influenced by what the people next decide you do. There's immense evidence this is true, even for very opinionated people it turns out to be true. So I'm going to beg you to try and close your eyes. We're not going to pull any funny stuff, and then I'll ask for a show of hands, for A, B, C, D, E, but the point of the closing eyes is a simple way not to be influenced by what other people do. OK, everybody, get the instructions, all right. So close your eyes. Hands up for A, got a rough count.

12:37

Hands up for B,

12:42

OK. Okay, hands up for C,

12:48

okay, hands up for D, okay.

12:53

So thank you very much. That was actually profoundly disappointing to me. This is a more educated audience than I thought. I was trying to lead you astray and lead you into a trap. And in fact, most of you had roughly the right answer, but which I guess maybe shows you you're doing really well. There were actually tests of another version of this done on MIT students, it's published in Science, that show that people routinely get this wrong. The basic kind of trick here is that, as you'll see in the next slide--I'll I'll just give you the next slide.

13:27

Maybe the most important single fact to know about climate change is that, over this century, temperatures are roughly proportional to cumulative emissions, to the total

accumulated amount of emissions. And so the way I was kind of implicitly leading you down the garden path was to kind of make you think there was some tight connection between CO₂ emissions and temperature. They're certainly related, but they're related through two steps in a causal chain that involve accumulating CO₂ emissions. And you want to be able to see that, because if CO₂ emissions go away instantly, let's say we could do away with all fossil fuel and industrial emissions tomorrow,

14:04

would temperatures go up or down a few years later? It turns out the answer is, they would go up a few years later. And we'll explain why that's true later, but it has to do with aerosols, and it's kind of central to the topic here. But if that's bugging you, think about it. But, but I was, I was hoping more of you would choose the wrong answer so that I could feel that I was justified at giving this lecture. But, but this, this fact, is the crucial fact. And let me expand on a little bit more. So I like to call this the first law. It's not a law of physics, and it's not exactly true. So actually, let me start with a caveat. This law works best for this century. It's an approximation of actually two different answers--I think Tiffany will get this a little bit--that are both slightly nonlinear in opposite directions. So it does turn out that temperatures are really quite linearly proportional to emissions, with quite a lot of uncertainty about that proportionality constant. But they are quite linearly proportional to emissions. But it's not that warming is actually not very linear in CO₂ concentrations in the amount of CO₂ in the atmosphere, there's some logarithm in there, and then there's some feedback on the carbon cycle that goes the other way. So the net effect is that things are pretty linear over the century, which is profoundly important for public policy. So this really is the number one law to say. And this law makes sense when you plot things in this way. When you plot things with the x axis being cumulative emissions and the y axis being temperature, the black is data and the data point here is roughly there, and then you've got projections for what might happen elsewhere. But the key point is that those two are roughly linear related, linearly related. And the answer to the questions I asked here is probably closer to A than B, depends precisely, but it's that I'd say, if you're going to choose one right answer, A is the right answer. And I'm kind of impressed by how many of you got A actually, I really did not expect that. Maybe something in the way I set it up, I don't know.

16:02

So that law has two important consequences, or maybe they're different ways to say the same thing. The first one is it just it's not a policy statement. If we'd like to see a roughly stable climate, then you must bring net emissions to zero. We can argue about what's

an appropriate time to do that. They'll clearly trade us about doing that quicker rather than slower, but it is pretty much a statement of fact. It's a statement of the cumulative emissions. The second thing is that stopping emissions basically stops warming, but it doesn't make it cool back down, so at any time you stop emissions, you're left with more or less the warming you had.

16:39

Here's two—a couple slides that just illustrate this point and tie to the fact you've got Dave Archer lecturing you next. It couldn't be a better next lecture on this. So this is one of the most famous papers that shows this long-term consequence, the irreversibility of climate change due to carbon dioxide emissions. And what it shows is that, if we—in their particular scenario, they were increasing emissions, I think, exponentially as I recall, and then stopping them, and I've got them stopped at 550 ppm, which is kind of like what we're talking about, and then they're showing you temperature projections out to 3000 years out. And you can see that basically it drops a bit after 1000 years ish, and then it goes out basically completely flat. And at that—I'm going to hold questions for now. That's a crucial and important result, and that's the result that David Archer does a beautiful job explaining in this public book. Really explain the details of it, this book called *The Long Thaw*, which kind of has a brilliant and evocative title, and he really explains some of the underlying science and why we believe the science we believe of that long thaw. But the punchline is that if we, if we stop all of these CO₂ emissions now, there are consequences that go out for 10,000 even 100,000 years, and you'll see some of the big glaciers melt for a long, long time after we stop.

18:06

So now let me come a little closer to the core thing I want to say about four dimensions. So this is the causal chain that underlies the climate problem. Economic activity drives emissions of carbon dioxide, the amount that comes out each year. This is this number in gigatons per year. The emissions build up in the atmosphere to make concentrations. This is an amount you may have heard as parts per million by volume. We're around 415 now or so. That drives the concentrations of carbon dioxide. These concentrations of carbon dioxide are what the climate system immediately feels. The climate physics feels something about the change in the infrared opacity of the earth that has to do with the Earth's atmosphere, that has to do with the increase in CO₂. Basically more CO₂ means it's a little harder for the Earth to radiate heat. It means for a given surface temperature, the earth radiates a little less heat, and so that means to come back in balance with the amount of energy it's absorbing from the sun, it needs to be a little bit

warmer to balance the books. That's kind of the key physics. We'll get to more of that, and Tiffany will get to more of how that works. But the key point is that what the climate change most immediately comes from is the amount of carbon dioxide and other greenhouse gases in the air. And then climate impacts are all these ways in which humans and natural world are harmed or affected by climate change, from extreme temperatures, to flooding, to sea level rise, what have you.

19:43

So there are four ways you can break that causal chain. So one way you can break the causal chain is by decarbonizing the economy, by shifting the kind of motor that keeps industrial civilization going from what it is now, which is mostly high, mid-80s percent fossil fuels, to some non-fossil energy source. I think that's going to be mostly solar, but maybe some nuclear. And this is going to break the link between economic activity and emissions. And I think--I will say quite a bit more about decarbonization in this lecture, because we're not dealing with it in the rest of this series. But I think the number one statement to say is there's no question we can decarbonize the economy. Lots of room for arguing about who pays and how quickly we do and what the trade offs are, but there's no doubt we can run the economy without CO2 emissions.

20:40

Carbon removal breaks the link between accumulated emissions, or historical emissions, and future concentrations, the amount of CO2 in the future. In that sense, I sometimes think about this as building the time machine. It's the way we could actually go backwards in time in terms of the way the climate looks. And here again, there's, I think, many more questions, but I think there's no fundamental doubt that it's within human ability with technologies we roughly understand today, not with some unobtainium that hasn't been invented yet, to remove substantial quantities of CO2 from the atmosphere. Not saying it's easy, and clearly there will be environmental impacts and tradeoffs, and we'll get to all that, but it's a thing we could do.

21:25

Then there's this thing called sunlight reflection, the idea that we could deliberately make the earth a little bit more reflective so it absorbs a little bit less sunlight. So that helps to balance the books between the amount of absorbed energy and the amount of energy going out. So then you reduce the amount of climate change. That does not break the link between carbon dioxide and all the consequence of climate change, but it

weakens the link. And I think you'll find out that it weakens the link surprisingly well, more than many people might have expected. And there's a bunch of different ways you could do it. The way, the one way that we best understand is that you could put sulfuric acid gasses that make sulfuric acid aerosols. Aerosol just a fancy word for a particle that's so small that it doesn't fall very fast, so these are particles that maybe half a micron in size. You could put sulfuric acid gasses into the upper atmosphere, where they make these aerosols and reflect away maybe half a percent of the sunlight. Just to give you some kind of specifics for this, we'll be getting to a whole lecture on this later, but that's the basic idea of sunlight reflection, and that would reduce some of the climate changes. That's a very short term, quick acting thing.

22:37

And then there's adaptation. All the ways that we could weaken the link can't break the link between the physical climate change, the changes in extreme temperatures, in precip frequency, et cetera, et cetera, and the impacts humans feel, or the natural environment feels by doing things like better air conditioning or changing work habits or what have you. Sure, quick question.

23:11

AUDIENCE MEMBER: I heard that when the jets went flying after 9/11 that there was a 20% decrease in sunlight?

KEITH: Definitely not that big. There's, there's a bunch of papers that try and see a signal, and they can barely see the signal. Short answer.

AUDIENCE MEMBER: So, just flying more jets isn't going to reduce the sunlight?

23:26

KEITH: That's a different statement. It's complicated. I'm not going to take any more questions now until the end, but I think the short answer on that which--this is a statement I can say with confidence, is that the climate impact you have if you fly during night is considerably worse than the climate impact you have if you fly during the day. That's now even built into some of the impact calculators, and that's because of this effect. But no more questions. Sorry, I'm just realizing if I do these questions as we will really kind of lose the flow. So sorry about that. So that's the core of what these four

dimensions I want to talk about are decarbonization, carbon removal, sunlight reflection and adaptation. Now I want to spend quite a bit of time. I still haven't really told you much about what these things are. I want to spend quite a bit of time really trying to demonstrate that they are distinct, that it doesn't make sense to lump them. That it really is a four dimensional problem. The things that I count as part of climate systems engineering are these two middle things, carbon removal and solid reflection, and that's what you'll hear a big chunk of this lecture series about. So in the rest of this lecture, I actually will talk a little bit about decarbonization and adaptation, because, for completeness, I need to, but the first thing I'm going to do is really try and explain that these can't easily be lumped because, to be clear, I'm trying to make a quite strong claim that they--well, of course, there's 1000s of individual methods underneath all sorts of individual little technologies that could help us decarbonize or help remove a little CO₂. I want to argue that that when you boil it down, that none of these can sensibly be lumped into the other and preserve kind of a core structure of the problem.

25:15

So first of all, I want to say that decarbonization is not the same as carbon removal. So let me first kind of concede an opposite statement, that it's obvious while emissions are large, nature does not care. Nature cannot tell the difference between a ton that you don't emit because you built a solar panel and a ton that you emitted and recaptured in some permanent way. So that's kind of a counter argument. Says that, like in the near term, maybe these things really look like two versions of the same thing. Obviously, that fact is only true until we get to net zero. With carbon removal, it's possible to go below zero and be taking carbon out of the atmosphere in the net which you can't do with decarbonization. But there is some trade off between them. That's a fair statement, decarbonization is mostly about supplying energy without CO₂, obviously. So it's about, most importantly, this unbelievable movement towards solar power that's just stunningly better than expected. But also about all the other ways we can run the economy without CO₂ emissions. Carbon dioxide removal is about a lot of different things, lots of different methods, but a lot of the methods that are most scalable are about intervening in the Earth's geochemistry. That's what you'll hear about from Professor Archer and Cael, the idea that essentially CO₂ is a weak acid. Carbonic acid is what it makes when mixes in water, and acid plus bases, and we've got abundant bases, make stable salts, and that's a permanent way to remove CO₂ from the atmosphere. And there's a bunch of different ways that we can do that that all rely on this fundamental fact that this acids can be neutralized by a weak base, which is in fact, what's happening naturally. There are also ways that we can directly pull carbon dioxide out of the atmosphere directly, and ways that we can do that indirectly, through trees. And I'd say in general, these technologies are pretty distinct, but one link between them is many carbon dioxide

removal methods use a lot of energy, and so there's ways in which, if you actually think about policy, they'd be coupled together, because if you run them off energy that's making a lot of fossil fuels, you haven't really achieved anything. You need to run them off energy that's not releasing a lot of CO₂.

27:31

Finally, I think in policy terms, they're deeply different. Well, we can all argue about how well we've done it. We're used to having some products that people want to buy in markets that produce some side effects that are bad for the environment. And the way we manage that is produce rules that say you're only allowed to sell that product under some rules about having low environmental impact. That's how we've regulated all sorts of things. And we can do that for energy as well, and we're starting to do that. And the point is, as a policy measure, that's something that fits together with the way policy has been done for a long time. And it basically says you guys are free to have economic competition and sell energy as much as you like. It's just there's a rule that you the energy can't emit more than X CO₂. That's at least similar to the way we manage lots of other problems. And that's how we could manage decarbonization. There's other ways, but it's one way we could manage decarbonization. I think it's fundamentally different from carbon removal, because carbon removal, in the end, is paying for something that has no immediate benefit to the person who's paying the money. You're paying for a global public good. And in that sense, it's really quite different than the idea that you should, you could pay for energy that's dirty, and maybe you pay a little more for energy that's clean, and there's some public good element about pushing you to pay for the energy that's clean, but still, the individual consumer or business or whatever actually wants to buy energy, whereas nobody, well, there are actually people who are waking up in the morning and seem to want to buy carbon removal and they're even paying people like my old company to do it, but it's clearly a little different kind of want, because it's not something they actually want for their day to day lives. So I think decarbonization is really in some deep way different from carbon removal.

29:16

Carbon removal and solid reflection are sometimes lumped together as in way we're lumping them together here as parts of climate systems engineering, and sometimes they're both called geoengineering. And there's certainly things that link them together, but I want to argue that they're deeply different, and so it's fair to call them having two different dimensions. So on the one hand, again, I'm going to offer you counterpoints. If you cool the world a 10th of a degree centigrade by having a little CO₂ in the air, or you

cool it a 10th of a degree centigrade by reflecting some sunlight, it turns out that certainly in terms of global average temperature by definition, you got the same outcome. And you'll be surprised, that at least in the short term, the reduction climate change you could get by doing the sunlight reflection is pretty close to equivalent, not quite the same as the reduction in climate change you'd get by taking some CO₂ out of the air. But that's only true in the short term. It's absolutely not true in the long term because of this long term footprint of CO₂, and it's not true as you do more and more. So we'll need to say that much more about this, except that these are really different. In the structure, in the kind of science, and also in the cost structure. CO₂ carbon removal is inherently a kind of commodity scale business. If we want to remove carbon, we have to physically remove carbon at a quantity similar to the entire fossil fuel industry. So that's something measured in billions of tons a year. And if we're gonna do that scale, it better be at cost that are kind of less than 100 bucks a ton, or nobody will pay for it. And that's a sort of giant commodity business. We can talk about how that might work, but that's the character of it. Whereas sunlight reflection is about little tiny tweaks to the Earth's system that, in terms of the amount of physical materials, could be very small. So you could, in principle, cool the Earth significantly with a flow of materials that's less than a million tons a year, so 1000 times less. And one of the kind of consequences of that, it turns out to be, is that, in general, that sunlight reflection is really cheap, cheap enough that probably the politics of it will not be cost benefit, but they'll be risk to risk, questions about who should decide and how we decide, but not really questions about whether we can afford it. And that way, it's deeply different from carbon removal. And then most of all, the difference is this accumulation of CO₂ emissions. Sunlight reflection just masks the problem. Masking the problem can be worthwhile, but that's what it does. When you stop doing the sunlight reflection, you've still got the problem of the CO₂ in the atmosphere, whereas carbon removal actually takes the carbon dioxide out of the atmosphere. In that sense, they're, I think, quite deeply different. And most importantly, they're deeply different in the politics. So with carbon removal, any large carbon removal project will have costs, obviously, and it will have some local environmental harms associated with the project. And on the flip side of that, it has more or less a pure global benefit. Taking the CO₂ out of the air, if you just magically take CO₂ of the air, that's a pure global benefit. Sunlight reflection, or SRM, is completely different. Sunlight reflection has, there's really no local problem, in the sense that most versions of it don't have a big local footprint, but it has, if you do a global version of it, it has quite global benefits and quite global risks, but it's not localized in the same way. So they're just deeply different things.

Finally, some people are tempted to think of sunlight reflection as a kind of extreme adaptation. I mean, not just some people. I've heard John Holdren, former science advisor, make versions of this argument, and I kind of see why they do. It does look a little bit like adaptation. If you want to think that adaptation is everything we do after the CO₂ emissions are there. But I think that they're just different things. Little connects them technologically, and they're really not connected in terms of the physical location or how they work. Most importantly, again, adaptation is all local. Adaptation means that you, in a local area, whether you're talking a farmer in Bangladesh doing things to reduce the risk of flooding from a cyclone, or you're talking New York City building sea walls, they are things where some local community at some scale spends money to protect themselves locally, and that more or less is independent with whatever somebody's doing somewhere else, which is deeply different from carbon dioxide removal or sunlight reflection, that both have these global consequences.

33:57

So that's the end of my kind of initial contention that there really are four dimensions here. Now I'm going to spend some time talking about decarbonization, and then I'll spend some time talking about adaptation, very briefly, and then kind of come back to this idea that it's four dimensions.

34:13

So first of all, another quiz. This is what I showed you before, is the trajectory of global CO₂ emissions. I'm not going to spend so much time on this quiz. Much time on this quiz, but think about whether or not you personally believe you would bet--in this case, you could bet financially--whether or not emissions will be higher or lower in 2030, just five years from now than they are today. So think about it. I'm not going to bother with the closed eyes this time. Think about it and see if you can make a decision. And then put your hands up if you think CO₂ emissions will be lower in 2030, 5 years from now, than they are today. Only a few of us. Put your hands up if you think CO₂ emissions will be higher in 2030 than they are today. Almost everybody.

35:00

All right, so in this case, in this case, there isn't a clear right or wrong. In my other case, there really is. The other case was a scientific case. For this case, I think most of you are wrong. I'd be willing to bet money most of you are wrong, but it's not a scientific answer. I might be wrong. We don't know. Let me give you some information. To

confirm what most of you think, there's this kind of idea that Antonio Guterres said, "We're on a highway to hell, and our foot's on the accelerator". It's going faster and faster. And you might even think that things are going to get even worse. There's all this evidence that we're building data centers like crazy, and these data centers are going to drive up energy use really suddenly, and this could explosive growth in energy use could increase greenhouse gas emissions and completely blow through the climate targets. So there are a lot of reasons to think that things might be bad, but there are some pretty strong counter arguments. Number one is the extraordinary spending on clean energy. So this year, the world is spending more than 2% of the entire economic output of the world on clean energy, which is utterly unlike what was happening a few years ago, utterly unlike meaning factors of four different. And it is beginning to change the energy structure the world meaningfully. And let me give you some headlines about that. So this is from a serious energy analysis, this not some like bunch of greens, this is a for profit energy analysis company, Rystad. I'll show you some of the basis of this. But their estimate is that emissions peak about now. China's carbon emissions appear to be going down as of today. Again, maybe turn around all you guys, put your hands up. Maybe right, and I may be wrong, but there's real evidence that they are turning around. Here's the actual data, and that's for emissions overall. The thing that probably is going to be the slowest to go is oil, and yet, even for oil. And here's not from some, you know, happy green group. This is from Eurasia group. They think that we're about around peak now, that China is going to begin, China's been flat, that it's probably going to decline a bit. India is going up, but they don't think the increase in Indian man are going to-- increase in Indian demand is going to compensate for the falling demand in China, and certainly by lots of measures, it's worth looking up this report, by lots of observable trade measures, it looks very stagnant. You also see that oil prices have not spiked in spite of a bunch of big disruptions in the last few years. And I think that tells you something important. Here's a little bit what the Rystad forecast looks like. It's a forecast. It might be wrong, but they've done a bunch of thinking. This tells you a bit about why this is the outcome. So they're predicting that by 2030, emissions are down, and my vote is, I put money on that. I put like two to one odds on that, personally. And what they think is driving it is electricity sector against a continued increase in transportation sector, but then leveling off of transportation sector. This may or may not be true, but, but I think, I think whether or not it turns out to be true by 2030 who knows. But I think the evidence that things are decelerating quickly is very real. I think nobody expected--let me be more clear--I wrote papers about how the solar learning curve was flattening, about how solar prices really wouldn't get low enough to be useful. I always liked solar PV, but I never really believed it would change the world. We are now seeing installations at a pace that it is hard to wrap your head around. We're seeing five--last year, a five gigawatt AC facility in China, built at a cost of less than 70 cents a watt. It just blows your mind, if you know the energy business. The pace of change is stunning. I came back from India a

few weeks ago, and you can see this at a scale that's really hard to wrap your mind around. So my view is, and in fact, whether or not we're exactly at the peak, we may bounce a little bit above it, but that emissions are basically plateaued, that we're not going to see a significant emissions rise. So while I would only give two to one odds on no increase, I'm going to give significantly higher odds that it never gets more than a few percent above what it is today. Again, I may be wrong, but let me step back and say what that means, if I'm right.

39:26

I want to really step back to big context we've had. We've had centuries of extraordinary economic growth driven by fossil fuels. It's 250 years, a quarter of a millennium, since Watt invented the big improvement--factor of two or three efficiency improvement on Newcomen steam engine. And some of you may recall what that steam engine was used for. Its first commercial use was pumping water out of coal mines. You cannot think of a better definition of a chain reaction. Like mines are in the earth. They tend to fill with groundwater. You want to mine the earth, you got to pump the water out, so you build a machine that's more efficient for pumping the water out, so you can mine more coal and drive the cost of coal down. And that beginning, I mean, that's one particularly important case of the beginning of industrial revolution that drove this whole world that you've seen around us. So now, 250 years after where you've seen this real tight connection between energy use--in this case, I plot it as CO₂ emissions, but with fossil fuels, they're more or less the same thing--energy use and economic activity have been tightly coupled together. Now I think we're going to see not energy use and CO₂ be coupled, but we're going to see CO₂ emissions be flat and begin to decline, and economic growth keep going. And I think it's important to say that's a giant change after centuries of something else.

40:53

Of course, that doesn't solve the problem. I'll remind you, number one, CO₂, climate change is proportional to cumulative emissions. Even if you bring emissions to zero, you still have the climate change and the fact that we're peaking, I think it's great. I think it truly is literally a turning point in the climate story, in the sense that it's an actual turn in the emissions trajectory. But while it is a turning point, there are a lot of other turning points to come, and it doesn't solve the problem. But I think it's something to really it's something to really think hard about, and I think it connects with the fact that we're more able to talk about these other ideas, about carbon removal and sunlight reflection, because it's more clear that we can do several things at once.

41:34

Let me just say a tiny bit about adaptation. I'll just go one slide. I should say adaptation is the only part of this problem I've never worked on much personally. And this slide is motivated by some time I spent in Bangladesh, just as COVID was starting. And it's just one example. Some of you may know that there was this cyclone in November 1970 that helped to be part of the well, helped to trigger, arguably, the war that helped to create what's now Bangladesh. It's the worst natural disaster--actually not the worst natural disaster of the last century, because the floods in China in the 30s were even worse--but it's one of the worst natural disasters of last century. Killed something like half a million people, just a horrific cyclone. And there was a cyclone in May 2020, just a little bit after I was there, and I actually talked to people who recovered from some earlier cyclones, and that cyclone had a higher peak winds and slightly lower storm research, but pretty similar cyclone in many respects, and it killed about 100 people. That difference is different kinds of social adaptation. One of the things that we saw up close is that people have cyclone shelters, which basically just mean schools and other things that are raised a little higher, and they have cell phone-based warning systems and a whole social network. That means that you're just not likely to see so many people die from a big cyclone. That's one of many examples. If I want to mention one other example, I'd say solar-driven air conditioning. Air Conditioning used to be something we thought of really just kind of for the rich world, but it is spreading all over the poor world now, as solar has got cheaper, as the air conditioning equipment gets cheaper, as people realize that air conditioning is not just a luxury, it actually protects lives and increases productivity. So I think there's a lot of room for adaptation, maybe more than people used to think.

43:23

So, coming back to kind of the end of the main thing I want you to take away from this lecture, I think you can't combine any of these things. I think these really are you can't combine them and still maintain key pieces of the structure of the problem that are real. And so my contention is that the solution space, in the words of mathematician of climate change, is really four dimensional. This is the space of things we can do about it physically. Obviously, there's lots of political ways that we might choose to do one thing or another, and there's all these subcategories of things. But these things really are there.

43:58

They're also not new. So the first report about climate change, which went to a top decision maker in the world, went to President Johnson when I was two years old in '65 and it's actually really worth reading because it's short. A lot of these recent climate reports end up being 1000 pages long, and nobody really reads them. If you're motivated, go back and read that Johnson report. They had the first really good climate models that were being developed. The first model with water was just a year or so later, but they already knew about some of it. They had the CO₂ observations. They had the CO₂ core geochemistry, and they could really think through what the impacts would be. And it's kind of amazing how much was there. The one suggestion they had for managing a problem, or two different variants were basically what we now call sunlight reflection. So these ideas are not new, but they are ideas that mostly weren't talked about for a long time. So I want to keep this mostly technical and not political, but think a little bit about the thing I showed you on slide seven, which was a paper that said irreversible, blah, blah, blah, climate change. It's one of the most cited and important papers. That paper by somebody who I think is an amazing scientist, that paper doesn't have the word geoengineering in it, so that paper got through review, and people cite it, and it says it's irreversible, and yet, if the rest of the lecture you're going to hear are correct, it's not irreversible. That's not to say it's easy to reverse. It's not to say we should do these things, but as a physical statement, it's just wrong to say it's irreversible. We can reverse these climate changes, either by removing CO₂ or by some reflection or some combination of them. That might or might not be a good idea. You guys can form your own policy opinions, but a matter of physical fact, it's wrong to say that it's irreversible. We absolutely have tools to reverse it. Saying it's irreversible is more or less saying some of these dimensions don't exist. They're things we can't talk about. And for a long time, that actually has been the view of many people in the climate community--that we shouldn't talk about these things. So I'm just saying a little bit about the political context here. You'll get lots more technical details in these lectures. But I think the core thing I want to leave you with is not that that we actually should do one thing or another. These are things where people have different values. There's not an easy answer. But I want to leave you with the idea that there are these things. And I want to leave you, by then, the lecture series with much more details about how carbon removal could work, about how sunlight reflection could work, about how we might intervene in ice sheets to reduce some of these climate risks, to give you a sense that this problem really can be solved in multiple different ways, and that it's a choice how we mix and match these different dimensions to get to some kind of climate solution. That's the core message that we want to leave you with.

Let me say a little more about what this Climate Systems Engineering is. This is a new phrase that UChicago came up with as part of a new effort to build this as a field, and that's what recruited me to help lead this new climate systems engineering initiative. And think some of the thinking behind that is that it's some kind of Venn diagram between climate systems science, these broader systems science that you hear lots about in these lectures, and kind of older, in some ways, discredited ideas about systems engineering, the idea that you should think systematically about goals and uncertainty and progress toward those goals and how you do them. And climate systems engineering is looking at that overlap somehow, trying to understand what are the technological possibilities, what are the risks, how we might govern these things, what are the social implications of these technologies that fit in this box. And the main technologies that we look at in this box are the ones we'll talk about here: removing carbon dioxide, reversing this long term movement of carbon from the Earth's crust to the atmosphere; or this sunlight reflection, which is the short term way to reduce some of the risks of accumulated carbon dioxide; or this idea of intervening in the big glaciers that could reduce the global sea level rise from carbon dioxide. I think I want to say a little bit more about some of the ideas underlying climate systems engineering. It's not new that humans intervene in the Earth system deliberately to change it. Agriculture is about changing Earth processes to some human benefit, to produce food and agriculture has less environmental impacts, and we adjust them in different ways. We are, as a species, have changed the nitrogen cycle, one of the big, major geochemical cycles that saves the world by an amount that, in some respects, is much bigger than the way we change the climate. So the protein in your body is made from these nitrogen bonds, and that protein comes, in the end, from ways that we fix nitrogen, take nitrogen in the air, which is just N_2 which is useless to biology to make it biologically active, nitrogen species that's done in nature, in lightning strikes and in some really specialized little organs called ribosomes that come in, especially leguminous plants, and some other things that it's very hard to break that nitrogen bond. So it's a really special adaptation that plants can do this. And that's the core the plants that do that, that allows nitrogen for all the other plants, because any plant that has a protein, anything that has a protein needs that nitrogen. So nowadays, humans make nitrogen artificially, fix nitrogen by the Haber-Bosch process, in a quantity that's about as large as all of nature, with huge consequences. We spread it around the Earth, and we make carbon dioxide, obviously, from fossil fuels. Some of you may occasionally shop for organic goods. I would argue that you cannot buy organic food on this planet because there may be other planets where you could, but on this planet you cannot now, because any farm benefits from the fossil carbon in the atmosphere. Cause that changes the way plants grow. Plants need it. And pretty much any farm, it's a little more fuzzy, benefits from nitrogen fixation. Actually, some are harmed by that. It's complicated, but basically, all

farms have been altered by that change in nitrogen. So there's no version of the world that doesn't have this.

50:17

I think if climate is engineering about something, it's about understanding places in the Earth system where humans need to manage actively, and where the right answer isn't just bringing the human intervention directly to zero. So I wanted to say a few more words about that. There are some kinds of things where the right answer is obviously just to bring the pollutant to zero, and we can do that. So if you think about, say, lead pollutant pollution, which is one of the just biggest things that had impact, people in my generation have several points of IQ lost from lead pollution in the US, enormous impacts. It's pretty clear the right answer is to bring lead into the emissions in the environment to near zero. You can think about that for lots of other things, but for managing agriculture, and I think for managing some aspects of climate, the right answer has to be more dynamic. We have to think about what our values are, what the technologies are, and what choices we make. We're not going to bring agriculture to zero. We certainly could alter agriculture to do more of what we want with less harm. And I think in some respects, the same is true of climate. And to me, climate engineering is about the process of thinking through the science and the social science of how to manage parts of the Earth system where the answer isn't simply to remove the impact instantaneously, or that's not a plausible thing to do.

51:37

Maybe one last word on that topic, very generally, I think it's important to distinguish between interventions that are trying to transform the Earth for some benefit and intervention that are trying to reduce the remediate human impacts. So if you think about different kinds of wetland restoration or reintroducing certain kinds of species, or removing rats on bird islands where they destroy bird populations. These are ways in which humans are now intervening in nature, not to make it better for humans, but to actually allow nature to be itself more. Whereas agriculture is a place where we're intervening in nature in order to make food, in order to deliberately make nature different in order to get the food we want, and these technologies in climate system engineering could be used either way. My view is that if we're using them to reduce the amount of climate change, there's a way in which they're more like these restoration efforts. They're not a kind of deliberate hubistic attempt to move the earth to some other state. There are ways that we could reduce the impact on the earth. But they could be used multiple ways, and it's not my choice how they're used.

52:49

This says a little bit about what this climate systems engineering initiative that I lead is doing at UChicago, which isn't necessary for this lecture, but it's a useful background to understand how those of us giving this lecture are linked, and why there is such a program at UChicago. We're hiring new faculty, we're hiring postdocs, we're doing research, we're trying to build this to be more of a field. So this ideas are not new, and there are people working on these ideas in different ways all over the world. What I think UChicago realized, and I give a fair amount of credit to President Alivisatos for leadership in this is that we need to think about this in a more systematic way, not dominated by any one person or idea, but making it more like a real academic field of study. And that's the kind of underlying goal of the Climate Systems Engineering initiative here.

53:38

So in closing, let me just take you back to what's going to come. This lecture was very much this high-level introduction about this idea that there's these four fundamental dimensions of climate, giving you some high-level picture. After this, we're going to get sort of much more into the details, I think, in thinking about these lectures, the lecture by David Archer and by Tiffany Shaw are both fundamentally science, big, crucial chunks of the science, in David's case, the carbon cycle science, more, and in Tiffany's case, the climate physics, more. They're the crucial chunks that you need to understand the other parts of the climate engineering story. And both those lectures will both teach you a bunch of the science, but also in ways that are sort of specifically tailored to addressing some of the questions that we have for climate engineering. And then these later lectures by Cael, by myself, by me and Tiffany, get into the details of how these climate system engineering topics work or don't. And then the last lecture will be a little bit more high-level, like this lecture, where we're going to try and deal with some of the controversies and questions in this field and understand where it might be going. Thank you very much. Happy to take questions.