0:03

KEITH: Well, welcome. You've made it to the last lecture. Tiffany Shaw sends her regrets. She's taken on some big duties at the IPCC, the Intergovernmental Panel on Climate Change, and she couldn't make it today. So it's just me, and let me tell you a little bit about what I'm going to do today.

0:27

So just to situate you, we've started with me trying to convince you that climate has this character of being a four-dimensional problem, or rather, the solution space for climate has four dimensions. And then we've talked a lot about background, and we've talked about carbon removal, we've talked about sunlight reflection, and we've talked about these glacial interventions. And today, what I want to do for most of the lecture is talk about how we might navigate through that four-dimensional space, how we might make choices over time about how to use these various technologies. That's the core of it.

1:04

But I'm going to start by actually, in a sense, something that's the continuation of the last lecture. So I'm going to start by taking some time to really talk through a bunch of the concerns about sunlight reflection. I had a bunch of questions with some concerns over the course these lectures, and so I'm going to give you a kind of overview of my attempt. It's only one attempt at a taxonomy of those con-concerns, how to organize them. So that's that you could think of more as a continuation of the last lecture. And then the big center of this lecture is really this idea about how we might go through these things in time, and at the end, I'll really turn to the more political questions and take more questions.

1:48

So without further ado, you know, these are just some quotes that give you a sense of how strongly some famous people feel about this topic, and I could find much stronger ones. And none of these actually are the quotes that pick up the fact that many people, on now believe that some versions of this are already happening, and they think of it as chemtrails or something like that. That's not, of course, true, but it's something that quite powerful people, including now some members of the US cabinet and powerful media personalities, are saying in public, and so it's part of this weird politics of this topic. But let me step back from the really kind of wackiness of public, of the politics to try and say something—now, why am I cutting off the bottom slide...to say something about the structure of a set of concerns about this topic.

2:45

So this is from an article of mine that was in Science four years ago or so that was a taxonomy. It's not unique. People can argue with it, but I tried to be kind of systematic about all the various concerns that I've heard about sunlight reflection or solar geoengineering, and they're really divided in these, are divided in these four top level categories. And I think what I'm going to do is go to a simpler version of this slide that shows more clearly that it is a taxonomy, and then talk you through what some of these concerns would be. And you should think whether there's concerns that you might have that aren't on this list.

3:20

So the first and I think most obvious, are the physical risks of sunlight reflection, if it was done in a way that was intended to be benevolent, or well intentioned. Of course, lots of things that are intended to be well-intentioned are still subject to accidents and incompetence, first of all. That is just a fact of being human. So any version of this that's done, even if the goal was fundamentally some measure of large-scale welfare, would be subject to mistakes. I think you've got to assume that, and incompetence, which isn't quite the same thing.

3:58

And I think you can divide the kinds of physical harms roughly into two top level categories. And that is exacerbation of climate change. That's where we do sunlight reflection with, of course, the goal to reduce climate changes, where reduce means move closer to the preindustrial or closer to some reference state. And in general, certainly for global average temperature, there's no question whatsoever that sunlight reflection could move you closer to some reference state. That—nobody, even the strongest critics, disagrees with, and there's no question you could do the same for global average precipitation. But the question is, all, what happens on a regional level. And the question is, will some climate changes in some regions be exacerbated, that is, moved farther away from some reference climate state, or farther away from preindustrial and I think the answer is, it certainly will be true. If you did large scale sunlight reflection, there will be some important climate variables in some regions where you will exacerbate climate change, even though the goal was to reduce climate change. So that's one, I think, maybe the most important large-scale category of concerns.

5:11

But the second, the first one, are all the side effects that come from the specific way that you reflected sunlight. So if you reflect sunlight by putting sulfuric acid in the stratosphere, there's a chain of things. First of all, the actual risks of the operation itself. You have flying aircraft filled with hydrogen sulfide or something. Those could crash and people could die on the ground from operating those aircraft. That's, I think, small compared to other industrial operations, but it's not something you would want to neglect. Then there's the health impacts of that material, because we know that sulfur has bad health impacts, et cetera, et cetera, et cetera, a huge line to ones that are quite uncertain.

5:49

And these aren't just about—I just mentioned sulfates in the stratosphere, but the same kinds of things apply to some of the other technologies. So if you do marine cloud brightening, which might seem to be a very safe thing because you're just talking about little sea salt spray added to marine clouds, the answer is that sea salt spray can actually mobilize iodine, which has various impacts in atmospheric chemistry, and this is inherently patchy, so it's likely to exacerbate climate change in some places. All these things have a set of physical risks. So all this is the physical risk of a benevolent that is a well-intentioned deployment.

6:28

Then there's a bunch of things which I've lumped together as broadly as injustice, where I think the biggest one, I think really the underlying concern that is the most common and deepest concern about these ideas, is what's called, I think, maybe not correctly, moral hazard. It's the concern that the presence of sunlight reflection, actually doing it, or just contemplating doing it, will encourage people to not put so much effort into cutting emissions, or to emit more carbon dioxide. And I think actually, it's important to divide that into what I think of as two really very different kinds of injustice, if you like, or problems. One of them is a kind of political exploitation effect. So if you think about the world divided into some entities, maybe particularly fossil rich nations or fossil companies that are always going to want to resist emissions cuts, even if the public benefit and the right kind of utilitarian decision is to cut emissions, there are some set of entities that it's against their personal interest to cut emissions, and so they're going to argue and fight politically every way they can to not cut emissions. And they might use, I think it's likely they will use the prospect of sunlight reflection to argue that emissions cuts don't need to happen, or can happen much more slowly. And that's a kind of political exploitation, because it's like one group against another.

7:51

But there's also a kind of collective addiction we'll get to this later, like, really from the core of this. But think if you think very short-term, sunlight reflection actually, I think objectively, looks very good if you think very long term, it doesn't. We'll get to that at really the core of this lecture. But if you're just looking in the short term for how to reduce the warming, it really works well. And if you're not thinking about long term consequences of building up CO2, you could really argue that it's better to just let emissions rip and spend a little bit of money to turn the sunlight down. But that's not a sustainable policy. But people are prone to think short term, and may be prone to be over optimistic about technologies and to push risks and concerns out to future generations. And so I think there's really two distinct effects. One is a kind of political exploitation, one group against another, and the other one is this kind of collective addiction effect. And I think they're different, but they both are important in thinking about this.

8:50

Then there's different kinds of injustice, and really you can divide them in two broad categories. Each of these has tons of things underneath it. One is a kind of procedural question of, what is the procedure by which the decision gets made? Who gets a vote, who gets to intervene, who's in control? And then separately, there's a distributive question of—whoever made the decision, which might have been some grand, very democratic decision, or might have been a unilateral decision by one powerful country or dictator—there's a question of, what is the actual distributive effects? Who's made better off, who's made worse off? The distributive injustice questions.

9:24

Then there's a whole separate category, I think, of ways that this could cause conflict. Could these things be used as weapons? Could they, in some way make conflict more likely, even if they're not directly usable as weapons, which I think, in practice is the case, they're not usable as weapons.

9:40

And then I think there's a set of questions involving kind of the interaction of humans in the natural world. Does this make the world more like an artifact to us, in ways that some of us might not like? I've talked about sunlight reflection, mostly with the goal of reducing climate change. But when you invent new technologies, or when new technologies arise, they can get used in a lot of ways. And these technologies could be used not to reduce climate change, but to drive climate changes in ways that some group of humans might prefer, or even might be better for humans overall.

10:16

So it's true that if you gave somebody the goal of maximizing the primary productivity of the planet—the amount that all the trees and green things around the world grow—if you want to maximize the productivity the planet, which you could look at as a good, you probably will actually want to have higher CO_2 in the atmosphere and a little bit less sunlight, so you have a not, don't have really high temperatures, and reduce the pole to equator gradient. That would be more like some climates we've seen where the planet was much greener with higher CO_2, say, 60 million years ago. So that's a thing humans could engineer, but that wouldn't be reducing impacts on nature. That would be deliberately altering the earth to certain human purposes, which, of course, is what we've done with agriculture, but this would be doing it at a global scale in a way that feels very different.

11:05

So this is some overall set of a way to organize what some of these concerns would be. And with that, I actually want to leave sun reflection specifically. So think of that as kind of addendum to the last lecture. And I want to come to the central thing of this lecture, which is thinking about how we might navigate through these four direction dimensions. And really, I'm mostly going to be talking about how we navigate through the first three, because adaptation is really different. Adaptation is fundamentally something that people do locally, where they spend money and resources to reduce some risks by building air conditioning or drought resistant crops or sea walls or what have you, and they get the benefit of reduced harms locally. And so it's really a local versus local thing which has less large-scale political implications. And there's not so much a question of, what is the collective human choice about using these whereas the other ones really are collective. All the other ones have some global implication. So I'm going to think, well, I say four dimensions. In practice, a bunch of this conversation is really about how to navigate through three dimensions. And the question is, really, what's the right order of doing these things? How should we compare and think about them?

12:20

And I'll start with the sort of simplest version of this, which is, if you just imagine climate risk versus time, if we did fossil fuels forever, if your plan was just to ignore climate change and do fossil fuels forever, then I think it's fair to say that climate risks grow without bound. It really is true that if you just burn all the fossil fuels you have, I think what is legitimately called an existential threat, extraordinarily large levels of climate change. Even in the lifetime of one person living roughly centered at this now lifetime, somebody like me, we are going to change the amount of CO2 in the atmosphere as much in a single lifetime as the change from the Paleocene-Eocene Thermal Maximum 55 million years ago, when there were alligators, crocodilians in the high Arctic. The change from then till kind of the cold period of the last few million years, that change in carbon dioxide concentration, we're going to make changes comparable that in one lifetime, it's extraordinarily fast what we're doing.

13:25

So that's the fossil fuels forever scenario. Then there's this fact that if you cut emissions to zero, as I've told you, different times, in different ways, but it's, it's easy to forget it, and it's easy to forget it in the political rhetoric, cutting emissions to zero doesn't eliminate the risk of climate change and some risks, like the risk of melting big glaciers, would actually keep going up even once we cut emissions to zero. Other risks would stay roughly flat as we cut emissions to zero. Removing carbon allows you to pull the CO2 back out of the atmosphere. It's the time machine, if you like, and it allows us to reduce the underlying risks.

14:00

And then one common way to think about how to use sunlight reflection would be to somehow cut the top of the curve off, basically to start sunlight reflection sometime before this period where emissions, where concentrations peak, and then stop sometime after. And so in this in this picture, sunlight reflection is a supplement that reduces the risk in concert with these other things, but that's only one of many, many ways to think about how to use this.

14:29

This idea—this is my drawing here, but this idea has been around for now 15 years or so. This is something that's now become very famous in the little world of sunlight reflection and carbon removal, the so-called napkin diagram. There was a report of the Royal Society, the UK Royal Society wrote a report in 208, I was a member of the report team that dealt with geoengineering, both sunlight reflection and carbon removal, and John Shepherd was the head of that report writing committee. And this does not appear in the report, but it was in the back of our minds talking about a lot, and John apparently wrote it up on some napkin. This isn't the literal napkin. This is some later version that John wrote up on some napkin a year or two later, and it captures the core idea that many of us have about how these things might be combined. So the idea that there's some—this is more or less like a diagram I showed before, but with different labeling, but it's important enough, I'm happy to show versions of this twice; this one, of course, has actual dates and actual temperatures, which the last one had nothing—but it shows you some business as usual idea, and then carbon dioxide removal reducing it, and then sunlight reflection reducing a little bit more, and then this idea that what's left over is kind of impacts and suffering. And I think it's a really useful way to think about it.

15:43

It's important to say that this is just one of many ways these technologies might be used. I think it's a way that many of us think, in a kind of utilitarian sense, would be the right way. But there is no single right way, and it really is one of quite a few different ways. There was a very nice report that the United Nations Environment Programme wrote, called One Atmosphere. That's the kind of probably best high-level report from a UN agency like this on sunlight reflection, and it had the following diagram in it, which I think usefully provides four examples of just the kind of high level way these technologies might be used.

16:21

So one way is the idea that we just use sunlight reflection instead of emissions cuts. So that is that we just decide we're going to stop it warming by having a rule that we're going to keep reflecting more sunlight while we keep emitting fossil fuels forever. That is a thing that could be done. To be clear, it's a thing where the underlying risk keeps growing. Among other things, if you ever stop, the risk is very big in different ways. You're moving, even if you keep the global temperature the same, you're moving farther and farther away from the original climate state. I think there's very strong consensus that this is a bad idea, but it is important to get out there. It is one of the underlying ideas of how sunlight reflection might be used.

17:02

Another idea is sunlight reflection could be used temporarily, without any carbon removal, just to slow down the rate of change. And that's important, because lots of climate impacts depend on the rate of change, just not the absolute. And so here I want to critique a little bit a common statement you hear from many critics of sunlight reflection, including, say, my colleague, Ray Pierrehumbert, who would say that once we start, we have to continue it forever. That is simply false. And this diagram, among many others in match analysis, shows that it's false. That is, one could start, ramp it up, and then gradually ramp it back down. You don't have to continue forever. I think the intuition when Ray Pierrehumbert made that statement is he's thinking like a long term geophysicist, and thinking that if we don't remove the CO2, the underlying risk is there forever. That's a correct intuition. He's very much right about that, but, but it kind of forgets the fact that climate risks do depend on the rate of change, and so even if you used it temporarily, that would have a benefit, even though it doesn't change the long term, doesn't change the kind of 1000 year climate change, doing temporary SRM would reduce the rate of change, and that has real benefits, even though it doesn't change the long term.

18:15

Then there's ideas that we just hold to some peak temperature, keep it to 1.5 or 2 degrees while we do carbon removal. Obviously, this curve doesn't have carbon removal. These curves do have carbon removal. And then there's ideas that we use it in the case of emergency, where we somehow use it very suddenly to cool things down. In general, I, and I think most of my colleagues, think that the most sensible, one of them is something a little bit more like this, but not with a sharp target, more with the curved one that I showed you. But we're just a bunch of scientists and academics. We're not the ones who are making the decision, and it's very unclear what will happen. And so I think it's useful to think through what these different possible options are.

18:58

So let me step back a step and kind of move a little bit into economics and policy and say, how quickly should we cut emissions? How fast should we cut emissions? So all of you may have some opinions about it, but what's the right way to figure out how quickly to cut emissions?

19:18

I think, from the point of view of a public policy professor or economist, the answer has something to do with balancing costs and benefits. So cutting emissions costs money. Yes, it's not as bad now as it was some years ago. We made enormous progress on solar and wind power and so on, which I've told you about early in the lecture. But even today, cutting emissions quickly would cost a lot of money, because you've got to spend money on rapid decarbonization, which you otherwise could have spent on something else, poverty alleviation or what have you. There isn't an infinite amount of money and resources. So cutting emissions quickly is not a free good. It costs something do. And at any given time in any given country, if you reduce emissions sharply over the next couple of years, there will be less money for other stuff, less money for consumption, or less money for investment into other things.

20:16

The benefit of cutting emissions is all in the future, and it's all global. Those two facts are crucial. So it's global because carbon dioxide is well mixed. So the point is, if I as a person cut emissions by some choice of my lifestyle, or a country cuts emissions, and then there's less CO2 in the air, that benefit is pretty much global. They don't capture the benefit. Very different than if I spend money to, like, protect myself from climate change, where I get the benefit. And it's really all in the far future, because the day that you've cut emissions, and as I told you, climate change proportional cumulative emissions, the day that you cut emissions, you don't get really any change in climate. That change builds up slowly over time. And that's the fundamental public policy problem, and you can talk about what's the right way to do it.

21:06

So the first really serious effort to do this in a quantitative way by people who think about comparing the quantitative costs and benefits, which is a thing that economists do, was Bill Nordhaus in a paper in 1992. And Bill has subsequently won the Nobel Prize for, well, for work, this work and others. And this is the kind of core paper in thinking through the costs and benefits of climate change. There's lots of additional papers, but I want to take time to kind of call this out. And it's not an accident this paper was published in ‘92. That's the same time is the Rio Summit, the global Earth Summit that was the beginning of the kind of formal process of the Framework Convention on Climate Change, which has kind of been the anchor of international negotiations around climate change.

21:56

And it's worth spending a little time, if you're interested at all, looking at some of these words, or these words that “Scientists have warned about the accumulation is likely to be bad,” “Scientists have warned that climate change is likely bad,” he starts out, “and environmental groups have talked about us doing something,” he starts out, but then he says, the question is, how to balance goods and bads? How should we—how should we balance this? And the core thing, one equation in here that you can see, there's lots more equations in this couple pages, but not very many equations—this is an economist equation which says that the goal is to maximize the sum of utility, kind of good stuff over time, over all people.

22:31

That's the goal if you were a benevolent dictator. And so this paper is a sense written for an audience of benevolent dictators, which is sadly, a kind of small audience. But I think the hope is that negotiators thinking about climate or environmentalists or whatever, or, you know, think in their head what a benevolent dictator would do as a guideline for what might be a good thing to do. But just to be clear this, this is the right formula for the world if you're a benevolent dictator.

23:03

And so he came up with this DICE model. And since this paper was published, I mean, at that time, there were a few people doing it, this has grown into a huge industry of what are now called IAMs, Integrated Assessment Models. And there's, most of the current people who run these models kind of sneer at this DICE model because it's very simple, and they've added a lot of complexity. And these models are actually quite important. They form some of the basis, or at least an anchor, for the international negotiations and for claims that people make about how quickly we should cut emissions. A variant of these things is used to produce these so called social costs of carbon, which have actually entered into US law and law and other places. In other places. So all these things are kind of tied together. And this is the original paper that did the kind of first version of it.

23:49

And I'll want to give you a sense of how uncertain all this is. So this is the very first paper. It gives you some little sense. This gives you some sense of what's in the paper. I think the important thing to say is these models, this DICE model, is ridiculously simple. It has something like 20 equations. I should have memorized the exact number before the lecture, but it's about that which, from the point of view of a climate modelist is very simple. The whole climate model here are just these equations. The whole climate model is just two equations, basically, one for the surface ocean, one for the deep ocean, that has something called this lambda term, which is the climate sensitivity—that's how much the climate kind of responds to added rate of heating—and then it has some carbon cycle model of these three equations for the carbon cycle model. These are very simple, but I actually think that simplicity is a virtue. I believe that none of these models can actually correctly predict the right answer because, partly because there's no global utilitarian optimizer anyway. I think these models are ways to tell stories, and they tell you something about the relationship of different terms, and as we'll get to pretty quickly, they tell you something about the trade offs of how we would navigate in four dimensions, but I don't believe the exact numerical answers to any of these, and so I personally like the DICE model because it has so few equations, it's really obvious what's going on. It's just a toy, but it's a useful toy to talk through this problem. And my view is that some of the much more complicated models kind of make you think that they know the answer better, but the underlying questions are so hard. These are questions of how humans should live on the planet that I don't think any economic model really answers them that well. But I wanted to give you a sense of how simple this was.

25:30

So now I'm going to move on to a version of the DICE model that myself and two colleagues, Maria Belaya and Juan Mareno-Cruz modified to explicitly take account of carbon removal and sunlight reflection, which weren't in the original Nordhaus version. And I'll just say a little bit about how we did it, but it's in the spirit of being very simple. So for carbon removal, what we did was ridiculously simple. I gave you a lecture about all the work that I did in one little company, and there's all these different companies and all these complexities. In this model, it all comes down to this. We have some marginal cost in dollars per ton carbon, of cutting emissions. And this blue curve is the blue curve in the standard, current version of the DICE model of what is the cost of cutting emissions? Basically, the more you cut emissions, the more it costs. And economists always assume everything's in equilibrium, so it doesn't cost anything to cut the first little bit of emissions, and it costs more and more as you do more. I think that probably isn't true in the real world. That's what economists need to assume. And what we did is we assumed that carbon dioxide removal starts being a lot more expensive than emissions cuts, which I think is correct. That is, if you want to save a ton of emissions now, it's almost certain that it's cheaper to just build some more solar power than to do carbon removal. But our carbon removal curve doesn't grow so fast.

26:50

And the key parameter in all of our model is this crossing point. What we assume is that for the first 75% the first three quarters of emissions, we assume it's cheaper to just cut the emissions than to remove the carbon. But for the last 25% we assume it actually becomes cheaper to remove the carbon and keep the emissions going. And the kind of intuition behind that is for say, decarbonizing this building. There's all sorts of ways we know how to do it, and we can do it more cheaply than taking the CO2 out of the air. But if you're talking about decarbonizing international aviation, it's very hard to beat fossil fuels for long distance aircraft travel, very hard, and it might be the cheapest thing to do is just keep using fossil fuels and take the CO2 out of the air in that example, which is a couple percent of global emissions, for example.

27:38

So that's the one assumption we make. We can argue about it. What I like about it is it's really simple and transparent what we did.

27:45

The story for what we did for sunlight reflections, is a lot more complicated. I'm just going to kind of wave at it. We use some clever, in our view, linearization of the climate response. But the point is, it really was built on some information about how climate models work. But the core thing is, we want to capture some way in which sunlight reflection is not perfect. The problem we have as modelers is the core DICE model, and this is the problem all these modelers face, really just assumes that damages are proportional to global average temperature, and we know sunlight reflection perfectly reduces global average temperature. So if you just naively go to one of these models, you'd say the model would just choose to do sunlight reflection and nothing else. But that's missing the fact that sunlight reflection doesn't work perfectly, that first of all, there's side effects, where there are health harms and costs of it, and also there's this exacerbation of climate change. There's a bunch of ways in which it's not perfect, and we kind of boil those down into two different categories of ways it's not perfect, just like the taxonomy I showed you. One is the side effects of the health impacts, for example, and the other one is the imperfection of it that we come down to an angle parameter. And I won't explain it much more, but I'll show you the consequences of that angle parameter. Excuse the change in background.

28:58

So this is the actual results of our modified version of DICE model, showing you over time—so it's now, the first curve I showed you had no axes, it was just a conceptual—this curve actually comes from an optimal model, which is based on a lot of reasonable calibration. So this shows you radiative forcing, which is kind of how much we're pushing the climate. This shows you temperature. Down here shows you time. This shows you how we're dividing it up. So this is basically the napkin diagram. Indeed, I'm kind of proud, I think this paper was the first paper to kind of reproduce the napkin diagram from actual economic theory.

29:32

And so in this particular setting, the model is just mostly doing sunlight reflection, and it's doing less mitigation and doing CDR late. And then this is for a particular setting of the angle. This is for the angle at 30 degrees. And to go through here, if the angle is zero degrees, that turns out to be saying that sunlight reflection is almost perfect. It means that, and in that case, the model just almost only does sunlight reflection. And then as you increase the angle, you can see it change. That just gives you some sense of it.

30:04

And there's a lot wrong with this. This thing. We don't have any constraint about starting slowly. Of course, in practice, of course, I don't think we should suddenly start sunlight reflection. This is just the simplicity of this model, but I want to give you some sense of what these results look like.

30:19

So this is one example with a bunch of assumptions that says something about the optimal answer. I don't believe any of the particular numbers in it, but I do think there's something, and I'm going to come back and spend a bunch of time on it, about the order and the dynamics that probably is very robust, and that's what I'll hint at now. And I'll come back to a few ways.

30:44

First, a little side diversion. So one thing is, once we've got this model that allows you to calculate optimal economics, then we can put uncertainty in it, and we can calculate, just for fun, what is the benefit of knowing more? What is the benefit of reducing the uncertainty about these technologies, because from the point of view of some optimal benevolent dictator, they've got to make decisions now, but they don't know exactly how well these things would work, and the decisions have to factor in their ignorance. And ignorance gradually goes down over time as we learn more. So I'll tell you, first of all, the simplest version of this, and then I'll show you a complicated version.

31:19

The simplest version talks about what some of you may know as type one or type two errors. So this is the sort of simplest underlying way to just to talk about the possibility of us being wrong. The thing that I think probably most of you are worrying about, the natural thing to worry about, is that we assume that solar geoengineering works. We think, ah, you know, looks like it works great. Then we plan based on it working. So that has been means we make choices about how quickly we're cutting emissions out of things based on it working, and then we find out that it didn't work. That's the overconfidence box. That's, I think, the obvious place to worry about.

31:58

I think it's important to say that there are, is another box that we shouldn't ignore. It's this underconfidence box. And let me tell you what that means. Suppose we now assume, which is in practice, what policymakers now assume that sunlight reflection really doesn't work. That is that it's high risk and uncertainty and so on. And then in 2050 or 2075 we do a whole bunch of, bunch of new science has happened. We know a lot more, and our children look back and say, man, sunlight reflection was never going to be perfect. It would have had side effects, but it actually could have reduced human deaths from heat and environmental impacts by a lot, and we lost the opportunity for all that benefit, and that was because we were under confident both those things are possible, and both of them matter. And I think whenever people leap to the fact that we might be wrong about sunlight reflection, they're right, but they have to forget the other side: we might be underconfident. And right now, we've effectively assumed that it's not working and we're not taking advantage of it.

32:56

I don't know what the right answer is, but we can use this big model that I won't go into detail based on the model I just showed you to actually do a version of this with real money. So this is where we've actually now had uncertainties in the same angle parameter, and this is the same kind of axis where we've got some original uncertainty and some uncertainty afterwards. But now these actually have real numbers and probability distributions. And I'm just going to give you the punch line. The punch line is that in our particular model, if you reduce the uncertainty in how much we know, how well sunlight reflection works, if you reduce that uncertainty by just a third, so have some uncertainty distribution and make the uncertain distribution 1/3 narrower, from the point of view of an optimal, benevolent public planner that's worth something like $4 trillion. I don't believe this 4.5, I don't even believe that it's four, but I think this actually captures the right order of magnitude. It's profoundly important to know roughly what it how well it works now, and that tells you something about the value of research into this. You can make similar calculations, by the way, for the value of knowing more about climate sensitivity, about how bad the climate impacts will be, and for knowing about the value of carbon removal. Basically, if you're going to plan over time, any planning over time depends on assumptions about the future, and knowing those answers better allows you to be a better planner.

34:23

So now I'm going to give you something a little simpler than this big optimal model that I think answers a maybe more intuitive question, and I'll come back to the kind of big, I think, really important findings of these optimal model both the one that I've been involved in and many other people have done the same. So one way to think about a simpler version of problem is assume all you want to do is reduce temperatures by a little tiny bit, let's say a tenth of a degree C, what an economist would call a marginal amount, at some future time, 2030, 2070, 2740, whatever it is, some future time. And then you can sort of think the following: if the goal is to reduce temperatures compared to what they otherwise would have been by this delta t just means a little bit, then you can look at the very simply, the future temperatures being the current temperature plus the warming from future emissions, minus any cooling from carbon removal minus any cooling from SRM. The real world has lots of nonlinearities, but it's a really simple way to think about it. And in this sense, sunlight reflection and carbon removal can be substitutes. They're both ways we could reduce future temperatures a little bit. And an interesting question is, what is the relative environmental risks of sunlight reflection and carbon removal if they're achieving the same amount of cooling? I think that's actually a quite profound question, and the answer turns out to depend very, very strongly on how soon you want it.

35:55

So I'll show you a couple slides, but let me give you a conclusion first. If you want to cool the world over the next many centuries, the next millennium, carbon removal is much, much, much less risky than sunlight reflection. If you want to cool the world over the next decade or so, sunlight reflection is much less risky than carbon removal. Let me show you a little bit about why that's true.

36:17

So suppose you just are building carbon removal machinery, whether it's direct air capture or things to put alkalinity in the ocean or some kind of special way to take CO2 out of the air, or whatever it is, you're going to gradually build a stock of carbon removal, building stuff over time. So you start investing in a capital stock. And when you do that, there's some cumulative removal. Obviously, the first day you've invested, there's no removal. So removal grows as the integral of this. And then there's some temperature change, which more or less the integral, but there's some time delays. And the net effect, maybe I'll skip this one--the net effect is, if you look at the ratio of how much capital stock you built, how much carbon removal equipment you built, how much money you spent on it compared to the amount of temperature change you've achieved, that ratio has this kind of one over x form, where, in the distant future, it looks pretty good. It looks pretty small because you've built this carbon removal equipment. It's had time to run for a century or whatever, and so it's had time to take the CO2 out of the air. You get the benefit. But in the short time, if you build some thing, some way to bury CO2 by digging holes in the ground and caking up biomass and putting underground--the day you build that facility, there's a bunch of impacts at that facility: supply chain impacts, people died building it, there's land use impacts. And there's zero environmental benefit, because the benefits only grow slowly over time. This is the core stock and flow problem of the of climate, and it's the reason for the big conclusions I got to. So basically, if you want carbon remove, carbon removal to lower temperature fast, the relative weight of all that kind of side effects of doing it becomes very large.

38:02

So I'm going to just say this very quickly, you can actually do this explicitly for air, for air quality. So as I've shown you a little bit in a previous lecture, putting sulfur dioxide in the atmosphere or putting sulfur gas to drop into the stratosphere, one of their side effects is an air quality impact. So we can actually calculate and be very confident about how many people might die from that because of all the work that's been done on air quality impacts of sulfur. But also we actually know a lot about if you spend money in the current economy to do something like building carbon removal machines, you can calculate what the emissions consequences and mortality consequences are from those using a kind of life cycle model of the way the economy works now. And you can calculate how many people die from air pollution, and you can make, compare the two. And the net result, which I won't show in detail, the net result is, is that, well, I'll show very quickly. The net result is that the mortality from cooling the world tiny bit for sunlight reflection, is tiny, even after 50 years, compared to the mortality from the carbon removal machines.

39:15

I don't believe those numbers that much, but the underlying time dynamics is very real. That's the reason why carbon removal isn't very useful for for cooling the earth in the near term. And that's an important conclusion. And to be clear, a conclusion that most people talking about climate change don't seem to hold, but I think it's actually a very robust conclusion. So just to say this simply, final slide on this, if SRM and CDR are used to achieve the same little bit of temperature cooling sometime in the future, then if this future date is a few centuries out, then SRM looks riskier than CDR. But if this future date is a few decades out, then CDR looks riskier than SRM. I think that's actually quite a robust conclusion over different kinds of SRM and different kinds of CDR. And it's a little different from the cost benefit thing I talked about, because it's looking at benefit versus risk.

40:08

So I think this both gets you to the same place, and now I'm going to really try and get you to that place. So this is the diagram I showed you before, but now I want to simplify it a little bit, or the simple version of it, and start to point out what are some key events in that time sequence. So the first event is when you start emissions cuts. And we have started emissions cuts. The world is cutting emissions now. So that starts first. The next thing in this sequence would be when you start sunlight reflection, or cell regime assuring. And so that's in this diagram, what it looks like. Next event is, is when you start large scale carbon removal. And that comes back to the fact that that cutting the first maybe half of emissions, it's cheaper to just cut emissions than to emit the carbon and pull the carbon out of the air, back to something I may have referred to before as the First Law of Holes. If you find yourself in a hole, stop digging. It's very hard to argue that, in a world that is admitting a lot of carbon, that the right thing to do now is to spend a lot of money to pull the carbon back out of the air, that same money is better spent preventing the carbon from going in the air. But that isn't so true as you, as you go further out in time, and we've squeezed most of the carbon out of the economy, then carbon removal starts to look really good. And so that's a basic fact I think you get, which is carbon removal makes sense mostly after we've done most of the emissions cutting.

41:34

So I've drawn this kind of arbitrarily there, but that fits with the actual diagrams I gave you with numbers earlier. Then there's this important thing, that's day zero, where, presumably we'll have global celebrations. That's the day where, where the concentration of CO2 in the atmosphere peaks and begins to come back down. That's the day of net zero, where there's no net addition of CO2 to the atmosphere. After that, carbon removal is gradually removing CO2 from the atmosphere, and then at some point after that, you stop solar geoengineering. That's one scenario for this, but I think it's one that is quite robust in terms of the time order.

42:07

So let me show this to you even a simpler way, which I think really gets at some of the disconnect in the way people talk about this now. So if you ask, perhaps most of you, if you asked most policymakers about their preference order, I think you get a preference order like this. Most people think most of all, they like emissions cuts, and then they like large scale carbon removal, not so much, but maybe they're willing to talk about it. And then they like solar geoengineering the least. And I'm not going to argue with that preference order. I think it's a perfectly reasonable preference order. What I am saying is that the correct time order is not that. It might be that we should never use sunlight reflection. I think there's perfectly reasonable arguments for that. But I will say that if we ever do use sunlight reflection, there are strong arguments that say the right time order is emissions cuts first, which are already started, and then sunlight reflection, starting early and only after that large scale carbon removal. That is very much not the standard answer, but I think it's, in fact, a robust answer, and people will gradually come to see it that way, even if we decide not to use sunlight reflection, I think it's quite deep that that's the right order.

43:24

So I’m going to wrap up pretty soon. Now, so far, I've showed you a bunch of these economic models. I showed you ours. There's a bunch of other ones, but, but again, all these economic models suppose that we're trying to go for some global optimal where central planners are getting everything just right. That is pretty obviously not the world we live in. And maybe it's more obvious now than it was five years ago. It feels a little bit like the world of for those of you who are old science fiction fans, I think I read this first in, I read this in 1970s London, England. This feels a lot like that kind of Asimov Foundation idea that these people, the Foundation, what was it called—the, the Foundation? No, I'm missing the words for the people. Harry Selden and the thing that he ran was some foundation that was the...Encyclopedia Foundation, that's right. That they could, they could actually calculate exactly how societies would evolve, and then nudge them to evolve in a better way. And I think nobody believes that version of it, but I think a lot of economists still give talks as if they were talking to somebody who really was a global optimizer, and as if we actually could globally optimize like this, and I think it's important to admit we really can't.

44:44

So I’ve only got two more slides. This is going to inch a little closer to reality. To start talking about the politics of this, let me compare two different problems, actually. Sorry. I mean, blank that slide. Don't need to look at this yet. I'm. Now, let me first get you to think about the problem of cutting emissions. Suppose you're all different countries. For each of you, if you spend money to cut emissions now, that's money that is out of your pocket that you couldn't have spent otherwise to protect your citizens or to get them better health care or whatever, and the benefits of that go to everybody, and mostly the future. And that is the essence of a public goods problem. That's the challenge of cutting emissions. And of course, we do solve some public goods problems. Humans are not do actually work together to solve—what's a public goods problem? At least partially, we build public goods. We build sewers, we build all sorts of infrastructure that protects us, even though each of us individually might say we just want to spend money to make ourselves better. We do manage these public goods problems, however imperfectly, but fundamentally, we manage the public goods problems by negotiations that try and somehow bind us to manage this fact, the underlying fact, which is each individual's instantaneous kind of choice of, should I spend more money on current consumption, or should I spend money on adaptation to protect myself from climate change, where I know if I put dollars in protecting myself on climate change, the dollars stay with my citizens and I bought some real protection, as opposed to spending money to cut emissions, where you've got this future diffuse benefit. But we do—we have managed these problems before. The global ozone problem is a good example where humans did act collectively to manage a global problem despite having some of the same character.

46:39

But these global public goods problems, the general expectation is that we underprovide public goods. Pretty evident, in my opinion, as a Canadian, that the US underprovides a bunch of public goods because rich people in the US would rather have the money themselves than have the kind of better public services that people in Europe or China or Canada enjoy.

47:10

Sunlight reflection is a really different problem. So public goods problems are very common and and emissions cuts are one of many public goods problems, and there's lots you can say about how we manage them. Sunlight reflection is really different. Now, suppose you're all countries that want to decide about sunlight reflection. You've all had some scientific studies and figured out what is just the right amount of sunlight reflection that you want. And maybe for a bunch of you, the answer is zero. You've decided the right answer is none. And maybe for you it's a watt per square meter, and for you it's two watts per square meter, and for somebody up here on the far left there, it's six watts per square meter, all of different opinions. And this would reflect real different national circumstances. The point is, if you're talking about a very hot country where the harms of current warming are big, in fact, the base state of a warm world is not very good. You might really prefer a colder world, whereas if you're a cold country, not so much. That's kind of an obvious way there might be differences.

48:04

So suppose you each have a preference of how much sunlight reflection you want, and suppose the cost of silent reflection is zero, and any country can do it for the whole world. That's not quite true, but it's not far off the truth. So it's not literally true that any country can do it, it's not true that i's free, but it's pretty close to free and really, any big country could at least start to do it.

48:28

So in a world where any country could do it and it's free, and where countries have different preferences, then what happens is, whoever wants it the most, well, they just do it. So the gentleman out there in the upper left, he wanted six watts per square meter. He does six watts per square meter. So he's happy. He's got what he wanted. All the rest of you are oversupplied. You have more than you wanted because everybody else wanted less, and all the other rest of you have to suffer under more. And so there's some deep insight here, that the underlying problem, and this formulation for sunlight reflection is a problem of oversupply. It's the opposite of the undersupply problem for public goods.

49:09

So this was realized by another famous economist. I was going to try and get away from economists, but this is recognized by Marty Weitzman in this quite famous and influential paper that talks about what he calls a free driver. And to be clear, Marty also tries to solve the problem. He offers a voting architecture for how people can negotiate to not be so oversupplied with some good like this. But I don't think it's the only good like this. So I mentioned this for sunlight reflection, but I think you could replace some of what I said about sunlight reflection with social media or various other things. There are lots of things like this, where the cost of supply is pretty cheap, but different countries have different amounts they want. And if unilateralism is possible, then the problem might be oversupply, and it's quite different from public goods problems. I'm saying this in a very theoretical way, but hopefully you can all think of very practical things. I mean, these come down to very practical decisions about how we remove the sewage, how we remove the garbage. There's all sorts of things where we have public goods problems, and there are things where we have this strange kind of oversupply, free driver problem. And I think it's deep in the in the SRM or sunlight reflection structure, the problem, that it has a bit of this oversupply problem, if you conceive of it the way economists do.

50:23

In practice, I'm not so sure that's true. I mean, in practice right now, my view, as you can probably tell, is that, if anything, we have an undersupply problem, we're kind of, there's so many checks and balances and so many reasons why it's really risky for any country to start climate engineering that we're not doing any of it, even though, I think there's quite strong evidence that doing a little bit of it would have pretty broad benefits.

50:47

So then we get kind of closer to the real world of politics, and I don't want to say much more about it, happy to take questions, except the following. I think that people, in thinking about the politics of these things often fall into two extreme, considering only two extreme cases, neither of which are very credible. So one thing that is said often and said even in professional papers by social scientists, is that we can't make decisions about this unless they're unilateral, unless everyone's consulted and everyone agrees, and there are many people who assert that, as if that's actually the right ethical rule the law they'd like to see in place is that there should be universal agreement, that these should be done in a way that has consensus. The other few people have is that this will be done by a single country completely unilaterally.

51:41

I think it's very unlikely that either of those is either what does happen, or even what, well, or even what should happen. Let me first talk about this idea of consensus. It's commonly understood in negotiation. If you go to a business school course on negotiation, if you have a unanimity rule, then any one player can do what's called hostage taking. Any one player—I want to pick on this gentleman, for sake of having somebody in the audience—who might actually have any feeling. They might privately think that sunlight reflection is a good idea. But if they know there's unanimity rule and there's some other thing they want, they want some trade policy, you know, they want more investment in AI chips, or whatever, they can say in negotiations, I'm not going to say yes. So the unanimous voting rule, the last person has kind of like infinite power, because they can block the vote, and then they can ask for some side deal. And that's why we don't use the unanimity rules for very many things. This is not a very effective rule. And I think there are a lot of broad reasons why unanimity is not the right answer. Also, that was a sort of theoretical statement. Also practically, it's just not the way we do anything. No important international decisions are made on this kind of unanimous rule. And while I don't love international relations as they stand now, and I imagine they could be better, the fact is, humans are muddling through lots of decisions that are made collectively, about how we manage space debris, about how we manage diseases, about how we manage monetary policy, about how we manage AI that are involved at least some real collaboration, despite not having some glorious unanimous rule.

53:22

On the other side, I think it's very unlikely that, if SRM is done, it’s done completely unanimously by one country. And here's why I think that's unlikely. Suppose you are the leaders of that country, and you've legitimately done the studies and done the consultations and really decided that there's really a lot of evidence that SRM, while imperfect, would actually be much better for your country, and it's really your duty as a leader of this country to try and move forward with SRM, because it will protect people from heat waves and make the crops grow better. Suppose that you're there. But you are rational. You don't—to be clear, I'm not talking about you being benevolent; it's not like you necessarily care about the people in the next country—but you're rational, and you know that some other countries oppose SRM. If you're rational, you want, you believe it's in the interest of your country, you know that some other countries oppose—even if you don't, in principle, care in your heart about what those countries do, you're going to act in a way to minimize their chance to stop you, and that way is going to be to form a coalition. You're going to form a coalition that is somehow likely to be politically stable, just out of the self-interest of getting your citizens what you think is the right thing for them, or what you've decided democracy is the right thing for you.

54:42

And so I think that it's much more likely that SRM happens, it happens from some coalition of countries. I think the interesting thing is thinking, what kind of coalition, how does it work? What makes it politically stable? And I think political stability is the big issue here. It's easy to start. The hard thing is, can it go on in a stable way? And how to deal with the fact that some countries are going to oppose, but lots of things happen where some countries oppose, but it just happens anyway. That's the reality of deals. It's a deal in a regular democracy. That's the deal in the, however you want to think about the international system.

55:14

So I want to end there and say the politics of this is extremely complicated, and people are—I think it's easy to find statements out there that say kind of extreme and very confident things about the way SRM politics would work, or politics of SRM and carbon removal, because they're coupled, but different. Most of my last conversation was just talking about SRM, but actually the politics are different, but they're coupled.

55:40

But I think the important thing to say is: we don't know. Humans really haven't made decisions quite like this before. While there are analogs, there's nothing quite like this. The international system is evolving, and I think you should be cautious about very strong conclusions about how this will play out. I've worked on this topic now, for 30 or 40 years. I've seen lots of evolution in the way this works. I think it's extremely hard to guess what happens over the next 20 or 30 years, let alone over the next 100 years.

56:13

So my view, a kind of simple view, is, to come back to kind of where I am and where our research program is, is that we should be cautious about overassuming the way the politics works, and the fundamental job, to come back to where we are in a university of academics and of researchers broadly, is to articulate as best we can what the benefits are, what the risks are, and what the consequences of some different political organizations would be without trying to pretend that we're the global benevolent dictators, which we're certainly not, and without trying to assume that we know a single right answer. So the one thing that I am never comfortable saying about any of these technologies is what ought to be done? What is the right answer? I don't think there is a unitary right answer, that is, there's no way, I'll end with this, to have some set of brilliant scientists and economists and people from the humanities and social sciences, to have some kind of box that's a technocratic box, which we feed all the facts in and which produces an answer that's the right answer. That is just not the right way to think about this problem. I know more about lots of the specifics of these technologies than many people, but my values are not any better than anybody else's, and I think that's important to be clear-eyed about that. And I think that's a place where academia has sometimes overstated how confident we can be about whether these things should or shouldn't be used. Thank you very much for listening.