JEFFREY C. GROSSMAN: Right? So here we are. See? Because what I want you to do is feel your oneness with modeling using computational quantum mechanics and the sun's energy. Right? That's really what I've been wanting to try to bridge, the applications of using the sun in renewables, and how that connects to ways of modeling electrons. OK? So I really want to get to this other topic that we started which is using the sun's energy to make electricity. OK? So I want to cover that today and a little bit on Thursday.

OK. Now, since I've made PSET 6 optional, I wanted to just discuss a few points from it to start with. OK? Because that's like closing the loop on our modeling of solids, and then we'll do a little more motivation on solar PV, and then we'll talk about how computation can play a role, as I said. OK?

So actually, I'm going to bring up the PSET here, and I just want to-- I'm not going to do the problems with you, but I just want to ask you how you might approach these problems, just to make sure that, as we close this field this simulation of solids with quantum mechanics, we have a sense of what you might do. The equilibrium lattice constant, how would you calculate the equilibrium lattice constant? Somebody tell me. Yeah?

AUDIENCE: Looking for the lattice which minimizes [INAUDIBLE]

JEFFREY C. GROSSMAN: And how would you look for that?

AUDIENCE: Change the lattice [INAUDIBLE].

JEFFREY C. GROSSMAN: OK. Yeah. So you could just like change the lattice right, and I have like lattice and the energy. And I do like 4 and 5 and 6, or maybe that's not a good enough grid. Maybe I need 4.5, 5.5. Right? And what would my curve look like, if I have an energy, energy versus lattice? What's it going to look like?

Yeah, something like that. I don't know, and the minimum, the equilibrium is here. Now, is that converse with respect to k-points? Well, that's something you can do the curve for different numbers of k-points. Right?

But now, what if I wanted to calculate the binding energy, or in a solid, we call it the cohesive energy? Why? It sounds cool. It's different. Yeah. You know what I'm saying. You were waiting for that. We got a big cohesive energy [INAUDIBLE] or no, that didn't have anything to do with. Yeah.

10 seconds, do you call? Do you call a foul with 10 seconds left in a playoff game? That's all I want to know. 10 seconds left. You play it out. Right?

I don't care if it was like the worst flagrant foul of the year, you let it play out. You don't call a foul with 10 seconds left in a playoff game. It's just not the right way to lose.

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: What's that? You're feeling it? Yeah. Unbelievable. Unbelievable. All right. How would you calculate that cohesive energy, the binding energy in a solid? Yeah.

AUDIENCE: So after you find the equilibrium lattice constant, you have the [INAUDIBLE] energy.

JEFFREY C. GROSSMAN: OK. That's an energy versus lattice constant.

AUDIENCE: Then you can make the lattice constant really, really, really large, and then you'll get, basically, so it's like an isolated atom, get that energy, and you've got two [INAUDIBLE]

JEFFREY C. GROSSMAN: I like that. Did everybody see that? Yeah. Let's see. If I look over here, because you know you love the nanoHUB, and you want to see something on it today. Ah! That's because I didn't turn on my-- wait a second. OK. Turn it on. So now, if I ask you how to converge the k-points, Sam, for the cohesive energy calculation, how would you do that?

AUDIENCE: Do exactly what I just did, and change the number of k-points, and see if cohesive energy changed.

JEFFREY C. GROSSMAN: And is the number of k-points that you need going to be-- what's that going to be for the atom?

AUDIENCE: Small, probably really just [INAUDIBLE] isolate that, just not really periodic.

JEFFREY C. GROSSMAN: Yeah. If it's really isolated, you shouldn't need more than one k-point for the atom, but the solid is where you might need to look at the convergence. Right? So you see, here's our tool, and here is-- it's actually already defaulted to silicon. Right? And so you can just press-- why isn't it-- this is just torturous.

OK, there we go, Simulate. There's two scroll bars, and I can't handle it. Maybe it's me. I don't know. I like to blame the nanoHUB.

So this is silicon. Right? And I did silicon, and I got a crystal. And I forgot to click to show me the structure, but it's this beautiful structure. OK? And in the output, it gave me 214.6 eV, 214.6. So my energy here, let's just say that was the right lattice is 214.6 eV, and now what did you say to do?

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: OK.

AUDIENCE: The lattice really large.

JEFFREY C. GROSSMAN: Lattice constant.

AUDIENCE: Maybe say, I don't know, 15 or 20?

JEFFREY C. GROSSMAN: 20, let's apply it too. 20 angstroms, and then anything else?

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: OK. Except I don't really need four k-points, but let's just leave it in. OK? Is there a way to tell after looking at the simulation one second if I actually should have had more-- if I choose one k-point--

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: And if it's wiggly.

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: I should try to converge the k-points. Because if the band structure is wiggly, it means there's something going on versus k. So there's a dependence on k, and if that's true, then I shouldn't be settling for just not testing the convergence. Right? I should at least try to increase the number of k-points to see if [INAUDIBLE] so here it is.

There is my crystal of silicon with really large lattice constants. So you see, those atoms aren't even trying to bond together. Is it large enough? How can you tell? Well, you could look at the bone structure.

Yeah, and what should they be? If these are really atoms, these are really atoms, then the band structure-- oh, look at that. Those are beautiful silicon states. Right? These are S&P states of silicon. It's an atom. Because I just made them really far apart, so they didn't feel anything from their neighbors. Right?

Now, I got an energy here of-- and I'm coming back to your question here in a second-- but I got an energy here of 203. OK. So I got an atom was 203, and let's just round it. I'm just going to truncate 214 and 203 is the solid. OK? So Sam, what do I do next?

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: And the cohesive energy is 11 eV. And then I look it up, and I actually see that it's 4.6. Because I looked it up, and it's been measured in experiments. What did I do wrong? The cohesive energy of silicon, from my calculations I did the solid minus the atom, and I find it's 11 eV.

AUDIENCE: Making sure you've got the right lattice [INAUDIBLE]

JEFFREY C. GROSSMAN: For the solid? Maybe not, maybe I was here, but I wasn't 6 eV off. I know that, but it's a really good point. That's one thing to check. What else? Yeah?

AUDIENCE: Did you converge to your basis set?

JEFFREY C. GROSSMAN: Did I conversion it? Very unlikely. Excellent other point to check. Probably could get me a half an eV even, or more, maybe an eV, but it's not getting me 6. This is actually a really simple problem here. What is my cohesive energy?

AUDIENCE: [INAUDIBLE] divided by 2.

JEFFREY C. GROSSMAN: Yeah. Why?

AUDIENCE: Because there's two [INAUDIBLE].

JEFFREY C. GROSSMAN: Don't forget that. Yeah. See, you have a certain number of atoms that you made your crystal out of that went into the simulation. Right? That's actually, when I give this problem, that's a very common mistake. Well, I guess I'm giving this problem, since it is a problem set.

So don't make that mistake. You don't need to, because now, you know. When you go to the input here, remember, this is my basis. My basis had a certain number of atoms in it, and so then that's what gets repeated.

So the number of atoms, or electrons from those atoms, in the simulation is for two silicon atoms, not one. So the cohesive energy I calculated was per two atoms. So if I really want the cohesive energy per atom, you've got to divide by 2.

Another way to get the isolated atom would just be to take-- a lot of people did this last year, is they just take this atom out. OK? And they change that to one, and they give a large lattice constant, and that's a perfectly legitimate way. It's the same thing, actually. You're basically just getting those atoms to not see each other.

But then, you had a cohesive energy with two atoms in the unit cell and an atom energy with one atom in the unit cell. You just got to keep track of that. Right? So energy per what? Per your basis. OK? Basic stuff of simulating solids.

OK. Any other questions? I may come back to the PV question in a little bit, but I just wanted to make sure we feel our oneness. OK. There was a question up here.

AUDIENCE: What is the principle definition of cohesive energy?

JEFFREY C. GROSSMAN: So the cohesive energy really, the feeling is the gluon between the atoms. That's the feeling definition. It's how strongly they're glued together. The actual quantitative definition is it's the energy of the solid minus the energy of the constituent parts which in this case are atoms.

But you could be looking at say in a molecular solid and then you might want to know the cohesive energy between molecules. Right? In which case, this would be-- and then, you've got to be right with your ends, and that's what I'm saying. Right? If you did your solid with two, then you need to have N times the energy of an atom. Or you can think of it as just energy of all the atoms together that made up that solid. Right? So just make sure the numbers work. OK?

Now, that's actually the atomization energy. There lots of fun names for it. Now, I ended the lecture before the quiz with this motivation, which I think is amazing that the Earth's total resources of oil, the 2 trillion we've used and the other trillion we want to use, is energy you get from the sun in two days.

I also very quickly said, well, I'm not going to talk about climate change, but I can't help myself. I have to say a few words, just a few words on climate change, because it's really important. And so I'm just going to spend five minutes. That's all, I promise.

OK. So how hot are things going to get? Here's an article. There's lots of articles since here, but this is a nice picture. So I took this from *Time Magazine,* and there's lots of predictions. And there's a really big range, and that's part of the problem.

Part of the problem is also that it's not about just warming. That is what's happening on average over the Earth, but that's why we really shouldn't call it global warming. We should really call it climate change, because the changes that happen are very local. Right? They're very different in different parts of the world. Some places are going to get colder. OK?

OK, and so there's lots of examples, and you can see things melting the size of Rhode Island and lots of really great images of what the changes in temperature do. Here's one I like, because you don't always think about the warming in this sense. But the changes in climate also change when things get eaten, like animals that eat trees, like this beetle. That's a really bad thing for this tree that can live a few weeks either before or later than it usually lives, and therefore, there are no predators around to kill it.

And already, in Canada, this is just an enormous disaster. So 411 million cubic feet of trees have been killed, and that's double the take by all loggers in Canada. So enormous problems can arise from climate change, and you've seen these kinds of pictures.

So does anyone know what the P stands for? CO2 emissions, how much we're putting out into the world. PgC per year, what's the P? Peta, peta, that's a lot. How much is that?

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: Big number.

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: 15th, 10 to the 15th, right? That's a whole lot, and this is from that fairly famous IPCC report which is actually a good read. It's kind of boring, but it's like Smil. Right? Has anybody read Smil's books? You should all read-- anybody?

Nobody's even heard of him? So Vaclav Smil has written some wonderful books on energy. OK? It's a little bit dry. I'm not saying it's a page-turner. It's not dialogue-driven. It's not a novel. It's not a romance, but it's very interesting, very well put together, some of them.

Now, if you want something a little lighter, there's*Without Hot Air.* Has anybody read that,*Without Hot Air?* Anybody heard of that? OK. That's free. You can just download that off the internet, *Without Hot Air,* I think. I'll remember the author's name, in England.

Anyway, this is how much CO2 we put out, and these are just what they did is they just said, well, if we turn it over quickly-- you see, because the amount of CO2 in the atmosphere is different. It's still going to keep increasing, even if we change our ways. And so there's going to be still an increase, and then it's going to come down. This would be the CO2 in the atmosphere.

And if we turn it over a little later, then we get the green. And if we don't turn anything over until the red, we go up to 1,000 parts per million in the atmosphere, and that's a lot. What does that mean? Well, it's hard to predict. It's very unlikely, in my opinion, we'll do anything but the red, if that. Right?

You can see these things. It's not that hard. You can look at the data, and you can actually see these are the famous measurements from Keeling. You can see the seasonal breathing, but you can also see the trends.

And you can even see where, for example, oil production slowed. You can actually see it in this curve. OK? So it's not hard to see anthropogenic connections to CO2. That's actually obvious.

I think the connection between that and temperatures has been debated more, but I don't think many people disagree anymore that there's a very strong correlation. And this goes back 400,000 years, where now I think a million years of data-- if you look at the ice cores, there are bubbles in the ice. I promise, I'm almost done, but I couldn't help myself, because it's important. Right? There are bubbles in the ice, and you can see in the bubble how much CO2 there was. Right?

These things get trapped. It's really cool. Right? Bubbles of air get trapped in ice, and they're there from a million years ago. And we can take them out and do really, really careful measurements.

And we can also get the temperature, because we can look at the ratios of different isotopes of the water at that time. Because the ratios of the isotopes of oxygen and hydrogen in the water at that part of the ice tell you how warm the water was on average. Right? Fairly robust, and you can see very strong correlations. This is where we are here. This is 373 from 10 years ago, and 1,000 is very likely to be where we'll be. OK?

OK. Now, so here's the thing. OK? I'm almost done. This is the guy who ran for governor. Anybody remember him? A couple.

I'm not taking a political side here, but what I don't like is when this issue gets politicized, which is ridiculous levels. It does on both sides, by the way, both sides of whatever you want to call it, the debate. Do you debate hard, scientific fact? Anyway, I can get eight professors from MIT on both sides of this issue, and no one in this room will walk away understanding what they said about climate change.

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: Well, yeah. So I'm not trying to make a statement about this particular politician, but I just want to make this statement to show how this gets distorted for political purposes. This is total nonsense. Right? This statement is absolute nonsense, and what he's talking about is there is actually someone at MIT who has argued in actually very strong ways that you need to pay attention to against a connection between anthropogenic activities and climate change.

There's one person. Most people I think do not fall into that camp. But this is the way that we tend to then just avoid the whole problem and not look at it anymore. Right? So I just think that's detestable, detestable. Yeah, why not? We'll go for it, and this is the reason. Right?

So now, this is on the other side. This is on the other side. So one side is forget about it. Nobody at MIT even knows what they're saying. Right? It's total nonsense, and then the other side is we're all going to die. Right?

Now, there's a lot of-- OK. So this is from Climate Works. There's some actually really good studies that have gone on. What happens when the temperature does go up? Because it will. Right? It may take a little while, may take longer than that, shorter than that, but it's going to go up. Right?

And as I said, it's not going up anywhere, everywhere. It's going to go up in some places a lot more, and in other places, it will go down. OK? And so species extinction, storms, droughts, all this, but whether you believe this side and you look into those studies, some of which are actually very well done and careful, others of which are not.

What you realize very quickly is this is not an experiment we want to run. Right? This is not an experiment we want to run. Right? So that should be one of the underlying messages that comes across that makes us at least, at the very least, take this very seriously. OK? So I could go on, and I won't, but I just had to say a few things. OK.

Now, back to solar PV. Any questions about my little climate change rant? OK. I'd be happy to talk more about that part of the problem as well, which I'm passionately, obviously, interested in.

Now, OK. So I said the motivation is that we get a whole lot of energy-- I said 140. That's 130, but anyway, it's around there-- from the sun, and we don't use much of it compared to that. And yet, here's how we get our energy today. Look at that. Solar wind, wood, and waste that's bio is this yellow sliver.

That's how we use our energy. Right? Most of it comes from, of course, coal, natural gas, and oil. And yet with solar, you wouldn't need much land. It's actually a pretty land-efficient technology. OK?

So if 2% of the US were covered with PV, with an efficiency of 10%, you could supply all the US energy needs. If 0.3% of the land were covered, you'd get all the electricity needs in the US met. 0.3%, that's compared with 40% for agriculture. OK? So it's not a land problem. It's not a land problem. OK? Just what's in between highways is pretty good.

Solar PV has a nice advantage over some other renewables, in that you can scale all the way down, all the way up. So that's nice, and if you add it up, you can just take a small amount of land in Nevada. They won't mind. Right? Who here is from Nevada? Would you mind?

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: Thank you. You see what-- but come on, there are some things there.

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: There's all kinds of-- there's arsenic life there. There's all kinds of amazing-- so now, if you took spots, if you had six Nevadas that were willing to donate just a small amount of land around the world, and you put them in places that are sunny, like Nevada, you get 20 terawatts, 20 terawatts. That's more than half of what we think will need in 2050. Yeah.

AUDIENCE: [INAUDIBLE] give an estimate something like this costs.

JEFFREY C. GROSSMAN: Yeah. There you go, $50 trillion.

AUDIENCE: Is that just [INAUDIBLE] or upkeep as well?

JEFFREY C. GROSSMAN: That's just getting it on the ground. All right? Well, you got a 20 year warranty. Yeah. So this is the PV problem. This is the PV problem, and this is why you don't see solar installation on the top of every roof in town and why we're not taking advantage of this enormous resource.

It's too expensive, and compared to other renewables and compared certainly to non-renewables, it's way too expensive. All other renewables, all of the renewables, except for like ocean thermal-- we're not going to do that-- are much less expensive than solar PV. OK? So that's the problem.

Now it's not just-- you got to look at it a little bit more carefully. So sometimes, you see these broadbrush statements, but you've got to realize that, of course, this is the issue here is one of grid parity. So it's about the cost of the electricity where you are, and that is quite variable. The cost per watt at peak hours is over here, and what you can see is that there are some places where there's a lot of sun and electricity prices are high. We're basically already at grid parity up there, like those places I used to live.

And then there are other places where we think that by within 10 years we may reach grid parity in a whole lot more places. So it depends, because solar PV isn't just about-- it's not just about the sun's average over the Earth. It's about really where you are. How much sun is there? That's why you can get I think the payback time in California is like seven years, and here, it's double that or something.

OK. So that's an important point, and so I just want to show this, because you see sometimes these like it would cost $50 trillion, so let's not do it, or it's going to be-- or we can do it, because it's all there. We should just do it. We see these big arguments. I think it's sometimes important to come down to more like practical ideas. Right?

And one way to look at this is just what happened there? I did not put that into the graph. If you look at, say, the percentage of electricity sold in the US at or below some price, and you look at-- let's see if this works. Yes-- and you look at just the 10% most expensive of that, there are all kinds of questions that come into this argument concerning what would happen to these higher priced markets.

But let's just suppose you could grab them at their current price. Then, the top 10% would get you down to $0.14, $0.14 a kilowatt hour. That's the price target.

So the question is, could we replace 10% of electrical energy in the US with PV at a cost of $0.14? That becomes the target. Right? Actually, now that starts to sound reasonable, not easy in any way, but more reasonable than replacing all energy or all electricity. One important point is it actually could be done. It could be deployed. OK?

But another really important point is actually, if anyone says I'm going to replace all of the US electricity needs with solar, ask them how they plan to store 90% of that energy. OK? The grid can't take it. The grid is not a battery. It sort of is a little bit, but it's not a lot. It can't do it.

It can't handle the storage that you would need right now, if you replaced everything with PV. And in fact there's no storage technology right now that exists that could handle it. Right? So keep that in mind, when your friend says from say Harvard, well, I have a plan. I have a business strategy. We're going to replace everything with PV. Ask them how they're going to store it. Right? OK. But 10% you could squeeze in there without inventing a completely new battery. OK?

Oh, yeah. This is a side note. We think a lot about our developing-- I think maybe I showed this. I don't remember. We think a lot about the CO2 in the developed countries, but this is really where the problems are going to be, is how they choose to do things. OK? OK.

OK. Now, we're going to talk about how a solar cell works and how computational quantum mechanics can impact this problem, this problem of cost really. And just to set the stage, I want to be sure. So this is what you already know this that-- let me get back to this. The sun, when it's above the atmosphere-- because you had these spectra in the second homework, and we talked about this.

If you're up here, then that's how much power you get from the sun. And if you're now when you're down here, then you have the atmosphere which absorbs some of that. Remember that causes dips in the spectrum, because you've got certain molecules in the atmosphere that just take all the light out of that frequency. Right? And then what we tend to do, usually when we talk about solar PV, is we say, well, that's actually not what you really get. What you really get on average is something like the sun coming through at an angle.

Now, why is that important? So this is the standard solar PV spectrum that you use. It's called AM1.5, Air Mass. So you take the air mass into account, and it's 1.5, because it's at 45 degrees. Why does that matter? Yeah?

AUDIENCE: It's at an angle [INAUDIBLE]

JEFFREY C. GROSSMAN: Yeah. Well, so definitely there's an angular dependence. That's absolutely right. There is an angular dependence of the power. Right?

That's the cosine. You've got a cosine function, basically, and interdependence of the power that the solar cell generates with respect to the position of the sun. But what else is going on, when I put the sun at an angle?

AUDIENCE: It's more [INAUDIBLE]

JEFFREY C. GROSSMAN: Yeah. It's more air to go through. Right? So that's why very often this is the power. This is the average. So there is more air to go through, less air to go through, more air to go through. Right?

And so we just have some standards. A lot of times, you take AM1.5 as the standard. It's what you use when you buy like a solar simulator, and you do the tests in the lab. That what we use.

OK. So now, we'll go through every single curve here and have a quiz on it. Yeah. No, this is actually-- so has anybody seen this graph? One person, two people, OK. This is actually, if you meet somebody in a dark alley someday. And you've got your panel, your solar panel, and you pull it out, and they pull theirs out.

And you want to know who's got a more efficient panel, who decides? Right? NREL, that's where you take it. You take it to NREL. Right? So you say, take it outside. Take it to NREL.

NREL is the National-- Does anybody know who NREL is? National Renewable Energy Lab, it's over in Colorado, not a bad state. And they do this very careful testing on all kinds of solar technologies.

One of the cool things here about this to me is, first of all, look at how many materials make electricity from the sun. Isn't that amazing? I get really excited about that.

Now, when you buy a solar cell today, there's a little bit of variation, but most of the time, it's made out of what? Silicon. Silicon, and in fact, look at here. There's different kinds, but actually, it's really multicrystalline. Single crystalline is a little more efficient but more expensive. So most of the cells you buy are multicrystalline.

So you can find it, and that's these squares here. And you can see that silicon has gotten better with time. The efficiency used to be there, and it keeps on getting better. And now, if you want to buy silicon solar cells, you can buy them.

I can't get 20%-- multicrystalline silicon, you can't get that on the market easily, but I can get about 18% cells. Actually, that's not true. Multicrystalline I can get lower cells. So these are like the efficiency that you could get at most, and then there's like what you can actually get in your product. Right? And there's a big difference. Right?

So these are like what the record has been in research labs, tested and verified by NREL, and then there's like now I buy it. Who can sell me it, and what's your efficiency? And it's always lower.

And for monocrystalline silicon, which is like the best you can do, that's here, you see that we're pushing what I'll show you is close to the theoretical limit of how efficient this can even do this process. But that's 27%, but if I buy it, 18% is the best you can get on the market of monocrystalline. Right?

Now, why is that? Why is there such a difference between the research cell and what I can buy today?

AUDIENCE: [INAUDIBLE] But then you also have the bidding process. You have interim [INAUDIBLE] mass production [INAUDIBLE]

JEFFREY C. GROSSMAN: Scale up, scale up is hard. So I can make like a little solar cell like this and send it off to NREL. And they'll mark it at 28%, and now I get $100 million from some happy-go-lucky VC. And I build my plant, and all of a sudden, there are regions like this in the cells I make, but most of the cell is like 10%. Right?

Why? Well, manufacturability, scale up, huge issues with solar PV, huge issues. OK? There was a spin off that I won't name names, where it was really exciting, because they were literally like putting hard drives in the toaster oven and getting out solar cells. And it was such a cool idea using old material from other processes, and little parts of those cells were so efficient.

It was really promising, but with the homogeneity was terrible. And that's because you need processes that can get you uniformity at scale. This does not tell you about that. Right?

Now, I love this area down here, where you have all kinds of new materials happening. So in my group, we work on the bottom of the barrel in efficiency, but it's really exciting. Because these are all different materials, where I think there could be big changes in efficiency, like materials made out of carbon, quantum dots. You can make solar cells out of quantum dots. OK?

Why would I care about those kinds of other materials? What might they offer me? Yeah?

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: Let's say, I can get them up here. Let's say, I can get a quantum dot cell. Let's look at my little legend there. Where are my quantum dots, the triangles?

Oh, they've only been around since 2010. How cool is that? And look at that curve. They're doing well.

If you have two points, you can make a line. Right? And if you extrapolate this, in just six years, they're going to be as efficient as silicon. Why do I care? Why do I want all these materials? Yeah?

AUDIENCE: [INAUDIBLE] less expensive or more easy to mass produce.

JEFFREY C. GROSSMAN: Exactly. Yeah. It's all about cost. It's all about cost. So new materials might give me different ways, especially like low temperature solution processing is a key. Right?

So silicon PV, you got to bake this stuff at like 11 times. You put it in the oven at 1,000 Celsius. Right? I'm just making that up, but it's not too far from that. Low temperature solution processing is much cheaper.

OK. Now, the other thing that you need to remember, and I'll get to computation in a moment, in a little bit, but I want to finish this overview of solar PV. The other thing that you have to remember is that the cost of solar cells is not just the material. So it is the material, but notice that-- so here's crystalline silicon. Most of the solar cells today are still made of this.

But notice the blue here is the cost of the module. That's like the material and the glass stuff, and then the green is the installation cost. The installation cost is actually more than the material module cost. So in solar cells, actually, that has become only recently the biggest problem is the installation costs. Even just 10 years ago, the module cost was twice as much as installation. Today, it's half as much. OK?

So you can see that, if I go nano, this means a lot of things. I can make cells that have much cheaper materials costs, but see they're not very efficient. So if I want to normalize my cost per watt, I got to install a whole lot more of them. So my green curve is really high. You see? Does everybody see that? So that's the balance. Right?

Now, the interesting thing is that, you see, one of the reasons why silicon PV is so expensive is, why the insulation is expensive, is because it has to be put on glass, and glass is heavy. Right? There are laws in this country about how much a worker can actually carry on a roof, and that limits, literally, that limits how big you can make a panel. OK? The weight is a real problem, and then there are other costs as well on they're called balance of systems that go into that installation cost.

But what if you could make materials that could be put on templates other than glass? Maybe then you could really change the installation, the paradigm on the installation. That's a big, big reason why we're interested in all of these. Right?

So these are all thin film. These are all thin film. This is thick film. Now, what can you compute because of this class to tell me why this is thick, and these are thin? Is it the band gap? What about the band gap?

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: Direct or indirect? And as a first thing, as a first approximation, is that band gap direct or indirect? indirect here, direct here, therefore, you can make very thin films. You can make amorphous silicon at a micron. You've got to make this at 100 microns to absorb all the light. If you don't make it that thick, it just won't absorb enough light.

Why isn't it absorbing light? The band structure tells you. OK? The band structure would also tell you, or these electrons states would also tell you, that for nanostructure PV, you can make them as thin as 50 to 100 nanometers and absorb all the light. That's how efficient they can be at absorbing light. OK?

So that is a really important metric, because if you can make them thin, then you can put them maybe on different templates that are flexible. Maybe you don't need a thick glass template. The solution processing is, obviously, equally or more important. Any questions?

There's another issue that I just want to mention that people, happy-go-lucky PV people-- there are a lot of them-- talk about, which is just-- I should say, don't talk about, which is just again this scale, this production scale. Right? We talk about how we're going to get to 81 kilowatt hours a day per person of solar electricity. That's from *Without Hot Air,* an analysis done in that book. That should be a target.

OK. So but the thing is that, you see, if you want to meet that target, then what you're going to need is you're going to need to get to like 100% of the US electricity generated by solar PV or close to that. And that would require being able to make 14,000 acres per day, and today, we make 14 acres per day. So this is the kind of thing, you got to look at these problems as well, when you think about the solar PV problem.

You can't just dream up a material and say, aha. Right? You got to really ask how it's going to fit in to the full problem. OK? So anything, any new technology, has to accelerate over the silicon production rate, has to be better than silicon. Silicon is a moving target, and it has to retire efficiencies and/or lower installation costs for different reasons, as I just mentioned.

OK. Now, this is one I'm going to skip, but I put it here for you. Because this is what I don't want to talk about which is the device view. This is what you'd learn in like a EE class. OK? And it's great, and it's a really good way to look at solar cells, and I've got two slides that summarize it. Basically, a solar cell is a diode that you shine light on.

I don't want to talk about that picture, happy to do so offline, after class, whenever. So this is the typical kind of picture, because this does not-- this picture does not let me take the viewpoint of electrons. That's where we're coming from in this class is, well, what does an electron do in this material at the scale of the atom, and that's the picture I want to start with. So I'm going to go down the level from these device models which are extremely useful, and I'm going to look at this picture. OK?

So this is the picture. This is what an electron, our precious electrons, our electrons. We now feel that they are ours in this class. Do we own electrons? Yeah? OK. I saw some doubt, but it's OK. We still have Thursday.

We simulate electrons, and that's what we've been doing. This whole part of the class how can you model the behavior of electrons, and in particular, what are the energies of electrons in a material? That's really been our key goal. OK? And this is how an electron in that landscape sees a solar cell.

Light shines on the material, and an electron's just cruising around, and then it's like, oh man, I just got hit by a photon. right? And then it's like, I better take that energy in, but we know that for an electron, when it takes energy in-- Oh, David MacKay is the guy that wrote *Without Hot Air.* OK-- when it takes that energy in, what happens?

Let's say these are filled. Right? This is my Fermi energy. It's going to jump up. That's what electrons do, when they take energy in. We've talked about that.

So that's what happened, and then, what did it leave behind? A hole which is the same as an electron, but not, but it's positive. Right? So that's a positive charge, and there's my negative charge. And that's what happened when sun shined, showned, shown, shown on it. And then what happens here?

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: Yeah. It relaxes. What does that mean? It's not taking it easy.

AUDIENCE: You go back down a couple.

JEFFREY C. GROSSMAN: To where?

AUDIENCE: There.

JEFFREY C. GROSSMAN: Here?

AUDIENCE: Yeah.

JEFFREY C. GROSSMAN: Right here?

AUDIENCE: Yeah.

JEFFREY C. GROSSMAN: Can it go here?

AUDIENCE: [INAUDIBLE] the one below it.

JEFFREY C. GROSSMAN: Here. It can't go in between, we know that. So it goes here, and that is the valence band-- no, Conduction Band Minimum, CBM, of the material. That's where it lands. And so just like in the solar field, what I wanted you to see in that third problem of the solar fuel homework is that you can excite electrons up, but you're only going to get out delta H. So you lose whatever energy.

When you hold something out in the sun, photons of all energies from the sun are hitting the something. Right? And most of them are going to just heat, wasted heat. Most of that sun's energy is wasted heat, and that's because of this right here. Right?

So this is just heat here. It's just heating the material, and then this is the energy, or the voltage if you want, that you can pull the electron out, that conduction band. All the other energy that you might have had is lost. Right? And so why don't I just make this really, really big, the gap?

AUDIENCE: [INAUDIBLE].

JEFFREY C. GROSSMAN: Yeah. Because if it's too big, if the gap is too big, then anything less than the gap doesn't get absorbed. If I make it too small, then boy, do I waste a lot of the sun's energy. Right? Then, I have almost no voltage. There's a sweet spot, and that's what problem three was about in PSET 5. Right?

Now, then the electron has to get out. If it's a certain kind of solar cell, it can actually recombine with the hole, which we really don't want. See, in some materials, like in Silicon, the electron and the hole really don't like each other much. They're Facebook friends, or I don't know.

What do you kids call it these days? They tweet. No, no, because nobody tweets. Who tweets? Does anybody tweet?

I'm amazed by that. I have no clue what I'm talking about. How many of you have a Facebook page? Right. OK. I'm just learning. It's a learning thing for me.

Google Plus? Google Plus? It's gotten better? Has it gotten better? Sort of. Yeah. OK. So fact of the matter is, where was I?

Anyway, they don't like each other much. They like each other a little bit, like a millielectron volt or two of binding between that electron and the hole in silicon. So basically, as soon as that electron and hole form, and one is in the connection band, and the other is in the valence band, they're like, eh, whatever, and they just wander off. OK?

Now, that's a weakly bound exciton is another way of saying that, or really not really much of an exciton at all, because there's exciton binding. An exciton is nothing more than a fancy way of saying electron hole pair, but in some materials, like polymer solar cells, which I will talk about, that's not true. You see, in some materials, the electron and the hole are very strongly attracted to each other. They are BFF. Did I say that right?

Best friends forever, except it's not forever, because you get them apart in a solar cell. You do get them apart, and it's sad. But then they go, and they do work, and then they come back. So it's a happy ending.

So now, when it's really weak, like in Silicon, well, you don't need much to pull them away. Right? You've got to pull them away. You got to transport the holes and transport the electrons over to some metals. And so actually, how do you pull them away? How do you get them out on the right side, different sides?

AUDIENCE: Electric field [INAUDIBLE]

JEFFREY C. GROSSMAN: Yeah. Yes, and yes. Right? A PN junction will do it, and even there, there can be whole regions where there's no field really. But as long as they finally get to some region where there is, and they can get off on the right side, we're good. OK?

But in other solar cells, and this is all within this picture. This is all within the same picture. We can talk about all these concepts. So in a silicon solar cell, recombination here is really not a problem, but this part is a problem.

That's really hard, because the indirect band gap. And then because you've got to make it thick, because that's bad, this part is a problem, because they got to transport for a long distance. And because they got to transport for a long distance, you got to make the material pure. So that it has good highways to get out. OK?

But in a plastic solar cell or an organic solar cell, well, these are really strongly bound. They really want to be best friends. There are half an electron volt bound instead of millielectron volts. Those are strongly bound excitons.

So a PN junction won't do it. You can't do that, because they're going to be together, unless you rip them apart. Right? And because they're going to be together, what's going to happen is, if you don't rip them apart soon, they're just going to collapse, and you're going to lose that.

All the photons energy, you're just going to lose, and the electron and hole will recombine. That's this recombination, and they'll emit a photon. Right? That's bad. That's a bad thing. Right?

So in those kinds of solar cells, the challenges are different. They're actually really good at this. Remember, I said 100 nanometers of thickness is all you need to absorb all the light in some of these materials, even less. OK? But where there is a challenge is how do you get them-- how do you pull them apart?

And the way you do it is you create interfaces, where when this electron and hole pair get to the interface, one of them really sees the grass is really greener on the other side of that interface. And the other one is like, I don't like that material, and then they split, and that's called a type 2 heterojunction. Which I'll show you a picture in a sec, in a little bit, or maybe Thursday morning. Thursday at the beginning of class, I think I might have time.

So this is the level that we can really understand solar cells from the fundamental electron viewpoint, and this is the level where you know how to compute relevant things. So tell me what you can compute that's relevant to this picture.

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: Yeah.

AUDIENCE: Fermi energy.

JEFFREY C. GROSSMAN: OK, Fermi energy. OK. So that would be for the metal. Right? That's the level that's going to try to line up with that level, and you'd like it to be pretty close. OK? What else? Somebody said band gap. Very good. That's this. Right? What else? What about the band gap?

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: OK, direct or indirect, very important. What else?

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: Mobility which is this part. How efficiently is it going to do this? Right? Well, you can calculate that now from the band structure. Right? What gives you the mobility?

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: Curvature of the band. OK? You know how to do that. And the last thing is that I'll just tell you because I'm going to show you in a second is that when you need to pull electrons and holes apart from each other, because they're really strongly bound, you need two different materials with a very particular way of lining their energy levels up.

So again, it comes back to-- there, it comes back to having one material with levels. This is, let's say, the HOMO in the LUMO, like that, and another material, or if you want to think about this is the conduction band and the valence band. You need to have-- if you have a really strongly bound electron hole, there it is. You're with me on this. Right? You see what I mean here.

This is a level. That was where it was. It's thermalized down, and this is strongly bound. So I got to rip them apart, and then that means I need another material with levels that come in at a very particular way with very particular alignment. And that's called the type 2 heterojunction, and if it's not type 2, you're not going to split them apart. OK?

Now, how can you calculate that? Well, you can calculate these levels. This is what you know how to do. So you can actually, with this same kind of methodology, you can calculate the levels across an interface. Exactly the same with the SIESTA tool you have, you can look at what those levels look like on one side of an interface, and when you change the material, what they look like on another. And you can tell me if it's a type 2 interface or say a type 1 or a broken junction or other kinds that wouldn't be good for PV. OK?

OK. So this is a very rich picture, and really, you can see that there are a lot of things you know how to compute now that are directly relevant to solar PV. So let's take a closer look. OK. So that's what we want to do is take a closer look at some of these. Any questions?

AUDIENCE: What is the [INAUDIBLE]

JEFFREY C. GROSSMAN: That's actually the conduction band minimum and the valence band maximum, and because sometimes the conduction band can be thought of as a band of states. But often, we only care about the very lowest one, which is where the electron is going to wind up. It's got plenty of time to get there. This thermalization process is super fast, super fast. OK?

OK. So this is again what I've been talking about, but I'll give you a few more specific examples. So in crystalline silicon which is still-- I don't know if it's 80%. Maybe it's between 70% and 80%. Right?

The band structure, the band gap, and the electron hole mobilities, this is all something we just talked about. OK? And it all comes from the band structure. So you get the band structure of the material, and these properties of the picture we just showed fall out. OK?

In amorphous silicon, see amorphous silicon is actually 3% of the market, and actually light absorption is really pretty good, and so you can make them very thin. That picture was-- where was it, there-- that's crystalline silicon. That's a crystalline silicon cell, and that's an amorphous silicon cell. And you can see one is curving, because you can make it really, really thin. OK? Whereas, if we tried to curve 100 microns, it's really hard to do. You're going to crack it. Right?

The problem with amorphous silicon, so electrons and holes also separate. That's not a problem. They separate easily. They're not strongly bound to each other, but here, you have the transport is the problem, holes in particular. Positive charges move very, very slowly through amorphous silicon. OK?

So they're actually, both electrons and holes, are a lot slower in amorphous silicon than in crystalline silicon, but holes are 200 times slower than electrons, 200 times slower. Right? Whereas, in crystalline silicon, they're only like two or three times slower. So that's a big discrepancy, and that causes big problems and a big drop in efficiency.

Now, what you can do with the calculations you know how to do is you can calculate the hole mobility, and actually, you can also calculate whether the amorphous material wants to trap a positive charge or not. And the way you do that is you simply, in the code, you simply calculate the structure with and without a positive charge in it, and you get an energy. Right? And then you can compare that from one structure to another, and try to understand something about why this material is trapping holes.

You see, in an amorphous material-- do I have a picture? I think I had a picture of-- maybe I have a picture later. Why would we want an amorphous silicon over a crystalline silicon? It's cheaper. Why is it cheaper?

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: Why?

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: Yeah. It's just a mess. Amorphous silicon is a mess. Right? It's a messy material. Now, there are still very important ways of doing the processing that can make a difference on the performance. Right? Hydrogen concentration, how you anneal it, but it's a much easier material to make, since it's inherently messy.

Now, that poses a real challenge, because now you have a problem that you want to fix, the transport of charges in a messy material, and it's really hard to characterize messy materials. Right? Beautiful problem for computation, beautiful problem. And we're talking about holes and electrons, so the only game in town is quantum mechanics. That's the only game in town. Right?

You got to get to the description that we know how to do now of where electrons and holes are in the material. And in the computer, you can make messy this way, messy that way, add a little of this, put a defect in, and you can calculate what that does all the way down to the scales of these atoms and electrons. And that would be extremely hard, especially in a material that's disordered, to do experimentally. So this is a great problem for computation. I love this problem.

Amorphous silicon has a wonderful problem called the Stabler-Wronski effect. Stabler-Wronski in 1977, they wrote an APL, where they showed that you make an amorphous silicon solar cell. And let's say you make it, and you test it, and it's 10%. And now you hold it out under the sun for two hours, and after that, it's 7%. OK? And it doesn't come back, unless you heat it up, in which case, it does.

What a great problem. Right? So you get an immediate 30% hit on your performance, when you have an amorphous solar cell, amorphous silicon solar cell, and that is a 30, 40 year problem, 30 year problem that is unsolved. I love problems like that.

Why? You hold it out under the sun, and because of the sunlight exposure, something's-- the mess is getting messy in a bad way. Not all messes are created equal. Right? How cool is that? At the atomic scale, the disorder is different, when you shine light on it, and that difference, the different disorder, means something really important to positive charges. What? Unsolved, very cool problem, computation can play a big role.

OK. Now, in organic PV, as I already mentioned, I mentioned this. So let me get to that, but look at this. This is that solar spectrum, and often we like to plot just several ones. So but these are just the sun, whether you're on the Earth or how you measure it, but now here's the key. This is the absorption of a polymer that can make an organic cell.

Now, you can see that one issue with organic materials is they can have really good absorption but in a fairly narrow range. So I can make this cell very thin, and theoretically, I could get a decent efficiency out of it. I don't by the way, but one would think I could. But you can see that I'm missing a whole lot of the solar spectrum. Right?

I'm missing a whole lot of the solar spectrum, and so that's one issue with polymers. Is they're very good at absorbing, very efficient at absorbing light, but usually in a fairly narrow part of the spectrum. So that's one challenge, and that's something that you now know a lot about, because you've been integrating this from like here back.

That was fun. Wasn't that fun? Yeah. I felt the pain. Sam, help me feel the pain. Inform me about the pain. OK.

Now, so that's one issue, and you know how to do that. You can take a polymer, put it in your nanoHUB tool, and integrate the sun from its gap. Right? And that'll give you this now, and you can even do it more fancy than that. You can even use the density of states to get a more realistic estimate of how much energy versus wavelength that that polymer can absorb.

But another really important problem that comes with polymers is that, again-- and this is exactly that picture I just showed-- you have to have two materials. Because in a polymer, when you excite an electron and a hole, they're usually strongly bound. Right?

So that exciton is a strong bound exciton, and therefore, you can't split them apart, unless you have an interface that has levels that align like this. So another really important part of polymer PV is to design the two kinds of materials that will give you those interfaces and then control them in some way to blend them. It's actually a really pretty hard problem.

There's a company, there are several companies, selling P3HT that is poly-3-hexylthiophene solar cells. Konarka, has anybody heard of Konarka? You can buy them, Konarka. A brave, bold move into polymer solar cells was made with $120 million by Konarka. I would say too early, but they're trying to push it.

Now, the problem is efficiencies are very low still. So you have these like they'll give you one of their products. It's like this size, and it's all packed in. And you can unfold it to the size of this table, because it's just flexible and thin, and you put it on plastic instead of glass. Right?

P3HD is a plastic. It's a cheap, cheap solution [? possible ?] plastic, and the films only need to be 100 nanometers thick. So you can put it on this flexible thing that folds up into a wallet, and you unfold it, and it's the size of the table. And you plug it into your cell phone, and you wait the whole day, and you get like two minutes of talk time. They're very low efficiency. OK?

But they're getting better, and actually the research efficiencies of polymer cells are now at 10%, almost 10%, 9%, 10%. That's pretty exciting. Remember, research efficiencies, what you buy is very different. It's still very low, 2%, maybe 3%. That's not what they say, but it's what people measure.

There's another issue with polymers though, with polymer cells. Can anybody tell me what they think it might be? What is that? Degrades, why? Two reasons, why do organic things degrade?

AUDIENCE: You start pulling apart [INAUDIBLE] from structure [INAUDIBLE] at certain points, it's going to become unusable.

JEFFREY C. GROSSMAN: Well, that's actually not-- you get them back, so that's actually not the problem. It's not that you're pulling-- It's not that you're depleting them or anything. It's a different problem.

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: That is absolutely the right answer for 3012, but in 3021-- well, it's still-- yes, I can't ever say no to the second law, ever. OK? So yes, but what else? What happens to polymer? There's two badnesses.

AUDIENCE: Oxidize?

JEFFREY C. GROSSMAN: OK. So oxygen is a tough one, water, oxygen. Right? Chemically they degrade. Now, how can I prevent that?

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: Packaging, you got it, and what does packaging say? What is really, really, really good packaging to really, really make sure oxygen and water doesn't get in? That should ring this in your mind, dollars.

That's expensive, and that's the problem, is now you're going back. Well, you had solution [? processable, ?] cheap materials, flexible substrates. You're hitting it out of the part, and then you've got to spend all your money on packaging. Right? And there's another reason why polymers degrade. Anybody know?

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: That could be where the degradation happens, but there's something else that happens to polymers, when you put them out in the sun.

AUDIENCE: [INAUDIBLE]

JEFFREY C. GROSSMAN: Why did car paint used to fade? It doesn't anymore. You guys are too young. Back when I was in school, in the 1930s, car paint used to fade. Why?

AUDIENCE: UV radiation?

JEFFREY C. GROSSMAN: It's UV. UV, right? UV is tough on us. Right? And UV is tough on organic matter, and so UV will over time degrade polymers as well. Now, there's still lots of discussion and debate, how much is one, moisture, oxygen, versus UV important here, but both are degrading this.

Now, when you install a solar cell in your house, what kind of warranty do you get?

AUDIENCE: 20 years.

JEFFREY C. GROSSMAN: 20 years, you got it. Right? And if it's a Cad-Tel solar cell, they'll offer to buy it back. No, they'll offer to safely dispose of the cadmium after 20 years. Yeah. I'll believe that when I see it. That's a very expensive business plan, but that's the kind of warranty you get, 20 years. And if you got stuff that's degrading in six months, which by the way you do, it's just very hard to compete. OK?

So those are some key issues degradation. Is not really as addressable with these computational quantum mechanics approaches we've been talking about, but I wanted to mention it, because it is a serious problem. So if somebody comes along and says, I have this great polymer that I think won't degrade. We can tell them whether it will still separate charge and absorb light. Right? So we can screen some key properties for suggestions.

OK. Is that band gap too high or too low? It's pretty high. It's pretty high. OK? Good. OK. Now, there's one other I'll talk about today, and then I'll finish this up. There's not much more I want to say, but I'll finish this up on Thursday at the beginning.

But another kind of cell that is really fun-- actually in a class I taught here to 2 1/2 years ago, we made these in class. We made dye sensitized cells. Has anybody made a dye sensitized cell? It's really easy.

Literally, you just take some TiO2, and we had a contest with fruit. We had the team pomegranate, team raspberry, and team blackberry, and you mash up your fruit, and that gives you the dye. Right? And that's just a light absorber, and then you coat TiO2, you coat your powder. OK? And you put it down on a metal, and then you put an electrolyte in, and I'll tell you what's happening in a minute.

And it's such a simple, cool fruit power, fruit power. Right? Solve the world's energy problems with blackberries which are like $6.99 for a pint. So that's scalable, not. But anyway, there are cheaper ways of getting dyes.

OK, but anyway, the point is that it's really simple and really elegant and actually pretty efficient. These are also known as Gratzel cells, because Gratzel was really one of the key founders of this idea, I think the key founder. And there are companies making and selling dye sensitized cells.

The reason they're appealing is they are actually even more efficient than polymer-based cells. They're up to I think even 14%, 15%. Again, the issue is packaging. Why? Because in this case, what happens is the dye coats a particle that is really good at pulling the electrons off.

Oh, you love these pictures. You know them now. You feel them now. Right? These are the pictures we use to describe solar technologies. Right?

So you have the dye, where sunlight shines on it, and an electron gets kicked up. Now, in this case, you see, you're not going to worry about moving that electron around in some slow polymer or amorphous material. You're going to put it into a TiO2 particle matrix, where actually electrons zip along really efficiently. So you really boost the transport part of the problem.

See, TiO2 by itself wouldn't absorb light very well, so the dye helps you kick the light absorption up. So that really helps. So the light is absorbed here, and then the electron transfers to the TiO2 and goes out here.

And here's the problem is you got to get that electron back, and the way you get it back is you get it back from the cathode, through a dye, through an electrolyte-- I'm sorry, through an electrolyte, I just read that word. Which is basically just shipping electrons from this metal electrode over to the dye. It's just an iodine solution, very cheap, very cheap, but it's just an electrolyte.

Has anybody heard of or worked with electrolytes? Well, even if not, it's OK. Right? There in lots of uses, and basically, what they are is they're a shuttle. It's atoms, I3's, molecules that are carrying electrons for you in a liquid.

What's the problem with that? Yeah. It's how are you going to keep that liquid in there for 20 years? 20 years you need a liquid to stay perfectly liquid. That's hard. Right? There's a lot of work that's been done on solid-state electrolytes for other applications. Right?

Lots of work has been done. It's an entire field that, if you had a good enough one, could be used here as well, but so far, solid-state electrolytes do not get you the electrons efficiently enough. OK? But when you use this very cheap liquid and very cheap dye and very cheap nanoparticles, you get a 14% efficient cell, and you can do it in one hour violating only a few codes, safety codes, in a classroom. OK? So it's actually a really cool technology.

I'll pick up here and finish the solar PV part on Thursday. Please, come to class, because we will fill out evaluations and have pizza. OK.