GANG CHEN: [INAUDIBLE], we talk about solar cells. So in the rest of this course, we're now shifting our attention to solar power. We're combining solar to this engine and particularly solar thermoelectric and solar thermal [INAUDIBLE] state. And so the-- here, what's important is not, of course, the [INAUDIBLE], but really have a system perspective. You'll find out the spectral control is really crucial for the overall system efficiency if you want to achieve [INAUDIBLE].

So let's review the three modes of heat transfer. This is the first class for mechanical engineering is very simple. But if you come from other field, this is probably the best familiar. But see, we know there are three modes of heat type thermal conduction from [INAUDIBLE] radiation. And conduction is the fact that through [? the ?] thermal conductivity, heat transfer rate. that's the power, and then it's proportional to the [INAUDIBLE] gradient.

And convection, we usually characterize with the [INAUDIBLE] coefficient h, so it's proportional to the [INAUDIBLE] difference between the wall and the fluids, which is away from the surface. And there are natural convection and forced convection.

And then thermal radiation, we typically talk about the Stefan-Boltzmann law for blackbody radiation. And then we calculate the heat transfer relation-- heat transfer between surfaces in terms of view factor and [INAUDIBLE], which we'll go more into more detail since we're talking more now on the radiation part. So the thermal radiation, Planck's law, is usually considered a maximum. And we define the intensity as the power leaving the surface in certain directions, so that the intensity is different from power.

So this is so that power in this direction that we will characterize by solid angle as a power in this direction per unit solid angle and per unit area normal to the direction of propagation per [INAUDIBLE]. So that's the intensity. So this is what we mean by intensity. It's propagating in this direction. And when we think about the area, this is the area, not this area, but the area projected in the direction of propagation. So [? ba ?] perpendicular has a cosine [INAUDIBLE] to the [? direction. ?]

And the solid angle is a measure of the angle in space. So if you think about 2D, we use a polar angle. And a [? parallel ?] angle is the arc [INAUDIBLE] divided by radiance. Or solid angle is the area perpendicular to the direction of propagation, [? eaj ?] here, and divide by r squared. So if you take a sphere in space, that's 4 pi r squared, your solid angle is 4 pi. In 2D, polar angle, the maximum is 2 pi.

So the solid angle is the space angle. And if we do [? a ?] into a polar spherical coordinates, this is theta, and [INAUDIBLE] with the direction to the phi, then you can show that this is a sine theta d theta d phi. So solid angle really including both theta and phi.

So that's the definition in terms of intensity. And when we want to calculate-- so intensity is a user starting point. In fact, it will be really interesting to go back and read the Planck's law. He had a very interesting discussions, very careful, interesting discussion about [INAUDIBLE] radiation intensity.

The immediate-- total immediate power of a surface normalized by surface area, that's what they call the emissive power. So now if you look at that, we normalize the emissive power. So power equals intensity times the area ea is perpendicular to the [? emissive ?] direction. So I have cosine theta. And d omega integration, so this is still per unit wavelength.

So that's the initial power. And for blackbody radiation, the intensity is isotropic. It's the same in all directions. So it's independent of direction. You can take this out, blackbody. And then you have cosine theta, d omega is sine theta, d theta, d phi. So you go to do the integration. And if we think about the integration, theta is from 0 to 2 pi. That's 90 degree. And phi is azimuthal polar, say, coordinate, the spherical coordinate, that's a 2 pi.

So if you do the integration, you find that the intensity for blackbody radiation for isotropic radiation, the intensity [INAUDIBLE] emissive power is a pi relationship. So that's the emissive power. And Planck's law of blackbody radiation could be either written in the intensity form or in the emissive power form. Apologize, I have a-- I missed the c square in my previous first lecture. If you go back to the notes, you can add that. So that's the intensity and the emissive power.

And so, this is what we talked-- pretty much what we talked before. And if you plot the blackbody radiation curve as a function of wavelength, usually it is a unit of micro per unit micrometer. And you find out the [? multiplicity ?] peak for a [? shift. ?] As it goes to a higher temperature, the peak shifts to a shorter wavelength. So this is a Wien's displacement law states where this peak happens is the maximum radiation state of [INAUDIBLE] wavelength where [INAUDIBLE] happens. And temperature is about 3,000. So that's the [INAUDIBLE].

Remember, and hence the solar temperature, [? static ?] temperature in a vacuum is about 6,000. So that's why our [? highest ?] is [INAUDIBLE]. That's [INAUDIBLE]. The evolution works really well here. And we have not, say, [? adapted. ?] So it's interesting that the human adapted the sensitivity to the sun. Not a lot at night that you're probably sleeping.

So if you think about the emission everybody has is [? 2 ?] micron. Because the 300 degree Kelvin has a peak around [? 2 ?] micron, which is equal to [INAUDIBLE]. So if you do integrate all the energy in this [? under all ?] wavelength, you get the Stefan-Boltzmann constant, 5.67 10 to the minus 8.

So this is pretty much what we-- a review. And now, I want to plug this into a more convenient form, blackbody radiation, because it's a function of two parameter, wavelength and temperature. But if I normalize this emissive power by temperature phase power, I change it to a small e meter [INAUDIBLE] change.

So if I normalize [INAUDIBLE] phase power, you find out this temperature phase power combined with lambda here is combined with lambda t. So now I only, I think about lambda t as one parameter. So this curve now, the blackbody [? uses ?] power [? localized ?] from pure phase power is [INAUDIBLE] function just lambda t. So I can have a universal curve rather than say each temperature have different blackbody curve.

And in fact, if you take your maximum lambda t, you can say, if you think this [INAUDIBLE] at the x, you find out where maximum is. That's Wien's displacement law. Wien got this by experiment. And in fact, you will see that the Wien had an [INAUDIBLE] [? too. ?] But this is from Planck's theory you can derive these things.

So now see, using this function, we can also calculate the fraction of energy. This is a very convenient [? particle. ?] In the old days, even now, for me, it's every time I want to see how much energy in certain wavelengths from the sun, I take this function and I look at table much faster.

So this is the fraction of energy between 0 to lambda. That's the integrate between 0 to lambda. And of course, using this function, we can say that eventually we could write this into lambda t fifth power of-- this is a force. So there should be another t here. And then say lambda t, t [INAUDIBLE], because here is the fifth power, here is normalized the fifth power. Here I normalized it only to the fourth power, because this is the total. That's the Stefan-Boltzmann law.

So after I write this, you can say, I can do this integration. this function is a function-- this integral is a function of lambda t only. Here is lambda t, lambda t, lambda t. So it's lambda t only. Again, so by doing this, I have a universal function that contains this is the fraction of energy with the wavelengths between 0 and lambda for any temperature t.

So if you give me a temperature, I look at the wavelengths, I do the multiplication, I go to check the table, and usually quickly you find out. So this is the integrand. That's the small f. That's here. And as a function of lambda t, lambda t is written in micron Kelvin. And here is the integral. So that's the fraction of energy between 0 and lambda t.

So you can quickly do an exercise. Again, let me take a solar energy, the sun at 606,000 Kelvin. A silicon bandgap is about 1.1 micron. So 6,000 times 1.1, 66, 6,600. So 6,600. If you look at this curve here-- this is a log scale, so it's harder to read. So the drop is 75%.

So the other 25% of the solar energy beyond the-- below the bandgap, which is longer, is not used at all. So that's the case of when you use a photovoltaics, there's a bandgap, and the photons below the bandgap does not electron [INAUDIBLE]-- does not excite the electron [INAUDIBLE] pairs. So that part is completely gone.

And in fact, you can also think for that part, it's better even just filter it out if you can do it cheaply. Why? Because if your solar cell absorb it, you will heat up the solar cell. And usually, solar cell heats up, the efficiency drop.

So that's the flat body. Now let's look at the sun itself. And then, [INAUDIBLE]. So the distance diameter of the sun is 1.4 2 to the 9, [INAUDIBLE] about 1,000,000,000 meter. Remember, diameter of the Earth, that's a 12 million or 13 million meters. And the distance is close to, what is it, 10 to the 11, 10 to 12. Is there a link for 10 to 12 for distance? [INAUDIBLE]. [? Parameter. ?] So 1.5 10 to the 11 power. So that's the distance.

And you look at the solar, of course, the orbital changes. The distance between the sun and the earth, slight change. But you see that this might be-- [INAUDIBLE] too large for you. But some of you may not be aware of this. Actually, in June and July, the solar flux is the lowest. From the distance, July is here, and it's the farthest away from the sun. Another thought is, this is the farthest.

So we have the lowest flux, but we have the summer. And the reason is not due to the distance, it's because the Earth is wobbling a little bit. When you surround the sun, if you look at it, the Earth's axis is not perpendicular to the plane of rotation. And it has a 24 degree of-- 22 or 24? So this is the direction [INAUDIBLE].

--23.5 degree from the normal direction. So this is the normal direction. And because of that, on each side here, the sun's atmosphere facing the sun. And here, the northern hemisphere is [? facing ?] the sun. So that's the tilting. And this actually created a problem. Particularly, we want the [INAUDIBLE] sun.

Say, some people do-- when we use concentration, you have to track your maximum. You want to maximize your intercepting area. And so, that's the tracking. You have to complete the rotation of the angle here of the Earth, of the [? orbit. ?]

So here is the blackbody radiation coming from the sun reaching the earth's surface. It's the outside atmosphere. And it's close to 58. Different people have slightly different numbers. Later on, I will show if I use a 5777 Kelvin, I get a [INAUDIBLE] constant very close to [INAUDIBLE] solar constant. So this is the-- it's very close to blackbody overall.

And of course, when the sun comes through the atmosphere, you have a lot of things happening. The solar radiation coming in, it will be reflected by the atmosphere. The clouds can scatter light to all directions. Some will go back.

And the atmosphere itself will absorb the solar radiation. Depends on what molecular species. Those are the vibrational modes of the molecules. Typically it's of the few micron range. So it depends on what kind of molecule you will have different absorption bands. So if the molecules are happily absorbing, or shooting around all of those molecules, then say those photons cannot reach the surface, it's the heat up the molecules directly. But there are transparency windows.

Again, this is a pretty lucky for us, for everything, just absorbed by all the molecules, we need to have direct sunlight and [INAUDIBLE] dark. And of course, there are also ways to reach surface. You will have the reflection from the surface of the Earth. So when you put a solar panel there, you have direct sunlight, you also have scattered light from the atmosphere and from the ground.

So this is a [? characterize ?] solar cell. People have to compare orange to orange. So there are standard in terms of what you should compare. And this solar spectrum [INAUDIBLE] by the air mass, which is the ratio of the [? confidence ?] of the air, of the air [? being ?] travelled through to the shortest possible pathway. So if I-- the outside atmosphere is an a m 0. And then a m one, air mass one, occurs when the sun is directly overhead.

And a m 1.5 occurs when the sun rays travel through roughly 50% more of the atmosphere than when the sun is directly overhead. So at an angle, there is, say, the confluence of the sun will be longer. And you can imagine, because the longer confluence, the spectrum of solar radiation reaching the surface will be different because the absorption of the atmosphere itself and scattering process.

So you look at, let's say, 1.5, the angular relation, the actual distance is 1 over cosine theta. So cosine 48.2 gives you 1.5. So this is, of course, a m 1.5 [INAUDIBLE] solar in this angle, the angle away from the perpendicular is 48.2 degrees. So that's the-- but there are also different [INAUDIBLE]. Depends on whether the solar radiation we measure is directly coming from the sun or there are also scattered, diffuse light.

So there are a m 1.5, there are different a m 1.5. I mentioned before, the a m 0 is the spectrum of the radiation outside the atmosphere. And a m one is directly 0 degree. And 1.5 has 1.5 [INAUDIBLE], g, and 1.5 direct [? path ?] circumsolar.

So the direct one is really consider a small cone of solar radiation. And this cone is confined to 2.5 degree, let's say here. Let's say 2.5 up and the 2.5 degree is around the sun. And so, this is the a m 1.5 direct. And then a m 1.5g is the radiation from the sun. The entire sky is reflecting off the ground. And so, in this case, the solar [INAUDIBLE] is 1.5 to the 40-- 48.2.

But also the panel itself is tilted at an angle of 37. So it's not a perpendicular incidence from the sun to the solar panel. Here is 37. So the angle of the incidence, angle of incidence is 11.2. And so, people are using 1.5g for solar cells. So that's just a property [INAUDIBLE]. 1.5 is the 40-- 48.1, 48.2. And so, the global equal the scattered light. And also, the panel is 11.1 degree away from the normal incidence.

So if you look at the spectrum, this is how the different gases in the atmosphere absorbs. And water is actually really the absorption is the worst. So this is the water absorption spectrum different wavelengths. Carbon dioxide here is 10 micron, That's about a 10-micron range. Carbon dioxide in this band is what people worry the most because of the increased carbon dioxide, the 10-micron radiation from the Earth cannot escape.

And in fact, if you combine all this, let's say the Earth warms a little bit more. In this, there are more water evaporate from the ocean, and more water will attract more radiation. So there is-- say, that's why it's a very complex problem. And methane [INAUDIBLE] oxide scattering is-- the scattering is the most severe in the blue region.

And that's why the sky is blue, because the scattering proportional of omega fourth power, frequency fourth power. So the short wavelength scatter more, and the sky is blue. We look at only scatter light. We don't directly look in the sun. So that's the solar spectrum, say, in terms of the absorption characteristics.

And here is the spectrum. So outside the Earth, you can see the blue curve here. And let's say when the radiation goes through the atmosphere, the absorption bands, different absorption bands here, will kick in, and the radiation is diminished when they reach the Earth's surface.

And if you integrate all the solar radiation here. And you get that the total radiation energy in the solar spectrum, and the a m 0 that's outside the atmosphere is 1,366 [? Watt ?] meter square. So you go to, say, probably I think Professor Ely Sachs, he has a startup company called 1366. Next time you can [? tell ?] when you saw him, that you know that's the solar [INAUDIBLE]. And this is a [INAUDIBLE] 577 Kelvin, so that's about a [INAUDIBLE], solar.

Now let's talk about the surface itself. And I'm giving you the next few slides of definitions. And the key point I want to [INAUDIBLE] not say you need to know all the details. But the key point is that the surface properties, radiation surface properties, is spectral dependent, depends on wavelengths, it's also directional dependent. So those particular data, we'll talk a lot on selective surface. That's the spectral dependence.

And in fact, they're also directionally [INAUDIBLE]. So control spectral and directional property of the surfaces. So the appreciation I want you to have is those are-- you can start with the basic property. When I look at the vicinity of a surface, I can look at the different direction on different wavelengths, how it's emitting the emission characteristics.

So this is the light coming, the intensity emitted in a certain direction. And I normalize the blackbody intensity. That's the-- usually we consider that as the maximum. So this normalization is the directional, which I put a prime, so notation-wise. And the spectrum, which I put a lambda, so directional spectral emissivity. And it's a function of the temperature of the surface, the material.

Temperature depends on temperature, depends on material, and also depends on surface finish. That's how we control the properties. You can have a piece of aluminum, which is a very shiny low emissivity, but you rough it, then your emissivity will change into much higher values. So that's a spectral direction or spectral.

And then you also allow you to integrate all the energy. So this is intensity. Here I'm talking about the energy now because it's a emitted [? in all ?] direction. If I integrate together all the energy going [INAUDIBLE] the surface, but still at a certain wavelength interval, only at a certain wavelength, then I get a half spherical. So that's an all directions, that's spectral.

And you can calculate. You can calculate from here to here if you know this, you know everything. We just want to go through the concept. And then you can also say, in this direction you integrate the whole spectrum. So we call that total, total is all the wavelengths. Hemispherical means all the angle. So you have direction total. And then formally, when you take an undergraduate course, you define emissivity, we typically talk about hemispherical [INAUDIBLE]. That's the typical [INAUDIBLE]. You look at a table [INAUDIBLE].

So that's the all direction, all wavelengths. So those are the definitions. And surface, when we say [? alpha, ?] it's in terms of the emission characteristics. If it goes all immediately in all directions isotropically, intensity is the same in all directions. Blackbody is the one example. It is a diffuse emitter, so it goes isotropic all directions. And if the emission is independent of wavelength, So the directional emissivity is same as if we integrate all wavelengths in the same direction.

So that's the [INAUDIBLE], the independent-- radiance independent of wavelength. Diffuse means isotropic. So diffuse grade means the [INAUDIBLE]. So if it's diffuse grade, then in all direction, all wavelengths is the same, and then all those emissivity are the same. But fundamentally, you can start from here and write the relation between all these properties to calculate all other properties in all this. But this one doesn't always equal to the others. So that's the emissivity.

And the inverse of emission is absorption. So if the light comes in, and the thermal radiation of light, and then the power, really-- I think I probably should have written d omega then in a small form how much radiation come in and then power absorbed in this-- the fraction of the power that's being absorbed in this small form. That's the absorptivity. And again, here we have, coming from a certain direction, so that's prime. And at specific wavelength, that's lambda.

So we define directional spectral, and then you do the same thing. You integrate [? all ?] angle of incidence. They absorb as hemispherical, spherical spectral. And then all in the same direction, integrate all wavelengths, or you integrate both wavelengths and direction, same analogous to emission, except now the reference is what comes in.

But let me just make one comment here. Although what comes in, the overall spectrum of-- so, for example, solar coming into the surface depends on temperature of the sun. But the spectral here doesn't depend on temperature. I can have the surface, this is [? thermal ?] radiating, coming to the surface, or this laser beam coming to the surface. That's my intensity. And this temperature is really the temperature of the material. But it's not a temperature of the source. So this is the absorptivity.

And then the next is a very important-- second law. Second law relation for emissivity and absorptivity. That's Kirchhoff's law. And Kirchhoff's law say, this is the same character of the object, the directional spectral absorptivity utility inverse directional spectral absorption. Blackbody radiation is not a second law. The Kirchhoff's law is a [INAUDIBLE].

The [? maxima ?] of the Planck's law, [? I am going to ?] say blackbody radiation, I mean Planck's law. You can break it. Kirchhoff's law, you cannot break it. This is the second law of thermodynamics. Fundamental, but remember, I'm putting down, again, directional, spectral. I don't mean the outer properties are the same. Now if you have a diffuse surface, diffuse emitter, diffuse absorber, then this is fine. Then say all the other property-- the higher level properties are also equal. But in general, they are not equal for higher order. It's only at this fundamental level, directional spectral.

So like I said, the message is, it's dependent on wavelength and angle. And if you think about the reflectivity, transmissivity, so you have a piece of glass. So light passing, you have reflection, and the light can go through. Of course, there are also [INAUDIBLE] here inside. And then the light comes in. The reflectivity is usually more complicated because you can go other directions. You can go-- when light comes to a surface-- and this is relatively smooth, but you can go to diffuse it to other directions.

So we then have to say, incoming is one direction, outgoing is another. So the fundamental definition is the actual despite directional, what comes in, what goes out is [INAUDIBLE] the intensity. So you have two angle. One is the angle of incident, the other is the angle of reflection. It's a bi-directional reflectivity. Let's say, now, if you integrate the whole reflected intensity, you get, say, the directional, when I say directional spectral. So that's coming in and integrate all angles.

So if, here, when I do bi-directional, notation-wise I have 2 prime. And when I integrate all angle of reflection, I get directional spectral. So this direction only means the incoming because I integrate the reflection over all angle ray. And then I have [? transferred. ?] So this now from here I can do the rest similar as I did for emissivity and [INAUDIBLE]. So in fact, there are eight. You can start with more fundamental and define all those other properties.

And you can do the same for transmissivity, bi-directional transmissivity, and then integrate over all transmitted light. And that's only one direction that angle of incidence. So all these are [INAUDIBLE] properties.

Now, the energy conservation will tell us, if I think about the light comes in, and it's [INAUDIBLE] reflected. That's the reflection of all angles incident at one angle, and absorbed it inside the material or transmit it to the other side. So that's an energy conversion. That's the first law. So in those relations, I've told you the first law and second law. Can't violate them in any of those-- in any cases.

So you've used reflector, so similar to the model we talked about, the emitter is when one light comes in, the reflected light go all directions, a really bad, say, surface in the sense of light goes all direction. But in fact, a lot of times you do want this, particularly in some illumination. You actually want the diffuse light that go to make the room feel comfortable.

And so a re-emitter is [INAUDIBLE] one wavelengths, and diffuse reflector is both isotropic and frequency-independent. So if you-- some of you, to the undergraduate heat transfer, learn diffuse [? resurface ?] means diffusive re-emitter and diffuse re-reflector. So it means both. We have come back to a solid diffuse re-emitter here with this [INAUDIBLE].

Now the definitions. We're not going to use much. I just want to make you aware that the surface properties are frequency-dependent, wavelength-dependent, and directional. And now, there's another key concept. When I want to calculate how much radiation goes if I have an emitter. Really, how much of my radiation get to you? So that's the concept of view factor. If I have one surface here, another surface here, view factor is defined the power leaving this surface. That's the total power leave this surface, and intercepted by this surface.

I didn't say absorbed by the other surface, it's just reaching the other surface. After which you could reflect it, transmit it, that's not including [? the power-- ?] say, the view factor. Just to say diffraction [? reached ?] [INAUDIBLE]. So that gives you a way of, if you think about the previous reflectivity transmissivity, that's near the surface. This is just saying how much goes to that surface.

And if I use this definition, the power within the surface here is the i [INAUDIBLE]. So that's the-- I should have multiplied the pi, I think. Yeah, so pi, that's because the intensity affects pi, the diffuse surface give me the total radiation leaving the surface. And then this is the radiation, if I go back to the definition of the intensity. So this is the power in the cone times the solid angle that this area, eaj, suspended with respect to this point here. So that's eaj cosine theta. That's the lower area. And divided by r squared, that's the distance between the two surfaces. And this is what's the power in this cone and reaching that area.

So this with this definition, I have-- I still [INAUDIBLE], I still think that needs a pi, but I will check that. So I have a pi r squared cosine theta i, cosine theta j, eaj. So that's a differential, small area, the two surface are small. Does anybody remember if this is pi?

And if I integrate both surfaces, I get a total [INAUDIBLE]. The surface is a uniformly [? medium. ?] And so, that's the view factor. Those kind of view factor, again, you can look for tables. One way to look is go to do this calculation, but a lot of standard geometry, people have done the calculation. So it's calculated.

And the assumption I made is that, over this surface, the radiation is diffuse. So I said I have a pi times i. And then radiation given the surface, the whole surface is uniform. So that's the assumption [INAUDIBLE]. And I said, you can look at the tables. But there are also relationships. If you look at the definition, it's very symmetric. So from this, you will see the reciprocity relation from view factor from a to j is times the area i. And then [? increase ?] from j to i times the area j. That's a reciprocity relation. And if you do the [INAUDIBLE].

And then the summation. Summation is basically the energy balance. The energy leaving surface i will reach j, combined surface i plus k. Then it's the same as leaving i [? plus ?] j and leaving i plus k. First [INAUDIBLE]. First one. So with those relation, the view factors, most of time you can, for simple geometry, you can find it from table, or you calculate using this relation rather than doing those complicated [INAUDIBLE] calculation.

Let's go look at the Earth and the sun. So the Earth and sun, because they are so far apart, essentially I can treat them a very small surface relative to each other, so the d area. And rather than look at the curvature, because if want to look at curvature, each point will be different angle-wise, perpendicular surface. And in fact, you can just treat this as a disk and this as a disk. It's the equivalent. The disk area of which pi d squared over 4.

And then I look at the view factor from the sun to the Earth. It's the Earth's area divided by the distance. So very small. And from Earth to the sun, so how much radiation leaving Earth reach the sun? That's the fraction. This is the fraction, radiation leaving the sun reach the Earth. That's here. There is the reverse. And because the sun cross-section area is larger, the view factor from Earth to the sun is larger, fraction-wise more radiation leaving here than here. So that's the [INAUDIBLE] first [INAUDIBLE] check the reciprocity is satisfied.

Now I want to calculate the solar constant. I said the 1,366, [INAUDIBLE] check. Radiation reaching the Earth from the sun, so this is the blackbody from the sun definitely by approximately the blackbody, times the surface area that is the area, a s, times the view factor from the sun to the Earth. So that's the total radiation from the sun reaching the Earth, intercepted by Earth.

And I can use the reciprocity to get a per unit area. Because the a s times the se, a s, se, [? fs ?] ae versus ae Earth, [? fe, es. ?] So when I do per unit area, I normalize, I use the reciprocity, I will actually write this as the sun emissive power times the Earth to sun-- here it's sun to Earth, but the area gives me the Earth to sun view factor.

Oops, I forgot this number. So this is a step, of course, [INAUDIBLE] minus 8. I was distributing an area. Sorry about that. Minus 8, 10 to the fourth power, that's this side, 5.67 10 to the minus 8, 577, that's the sun temperature, times this factor here, [INAUDIBLE]. I did the calculation. What I got is the 1,365, pretty close. And solar is constantly integrated. It's not exactly blackbody. So this is why some people say the equivalent is 5777. Solar constant is 1,366.

Now let's look at-- so that's the energy coming from the sun to the Earth. What's the maximum efficiency I potentially can get? What's my best [? luck? ?] If I can convert the solar energy into mechanical or electrical energy, the maximum using thermal process, thermal energy. Thermal energy, of course, is limited by the Planck's law-- or no, the [INAUDIBLE] efficiency.

So you can always say, it's the Earth's temperature and the sun temperature. You drive a power efficiency between the 2, and you will get 1 minus 300 divided by 5777, which is about 9%. That's an upper absolute, absolute possible [INAUDIBLE] you can somehow [? tap ?] into the sun directly.

Of course, we can't put anything in contact with the sun. And so, let's dream up this process. I have a blackbody of the sun very close to my absorber. Let's say, this is the-- I have a very close, because in reality, it can be close. But I can focus it, focus the solar radiation. And it turns out that if you do the full version, and the maximum you can get is something like the solar temperature.

So the blackbody at the sun, and the absorber, if I absorb all the solar radiation, so here the absorber is also a blackbody. And then say, I discovered a t, and then I put a engine in between this absorber and the ambient and the output. And then I can imagine this engine is a perfect car engine. So what will be the efficiency of such a, say, system?

And first I want to see how much heat can go from the sun to this absorber. Here, I'm doing to blackbody, so blackbody radiation is from sensing my T fourth power. You can see, now I don't have this very small view factor. I'm just doing two parallel plates. So sigma T fourth area is an [? no ?] area difference anymore. Sigma T fourth power minus this radiation, now the absorber will radiate it back. So [? minus ?] T fourth power. So that's the heat transfer from the sun to this absorber, maximum you can get.

And so, that means the thermal efficiency, what comes in, this order, this sigma T fourth power, and the amount of heat transfer that actually should happen is T fourth plus [INAUDIBLE] fourth must T fourth The thermal efficiency to the 1 minus [? come ?] to the fourth power ratio. So the higher the temperature the absorber, the lower is the thermal efficiency. And now, [INAUDIBLE].

So the power efficiency is here. And in fact, as I move on, you should ask questions. Because what are the questions, what if I use selective surface? Why you put a blackbody here? And this will be related to what kind of concentration, how you concentrate. Because here I'm really putting the maximum temperature. Really, this is the sun, this is blackbody, and they are facing each other. And that will require you to put your maximum concentration.

And in the case of maximum concentration, the emission of this surface becomes not important. It's really the absorption that's most important. Absorption, the higher the better, the best is 1. So you get a blackbody. That's why.

So now I have a thermal efficiency, I have a power efficiency, and the product of the two gives me the maximum-- the combined efficiency. So this is the thermal efficiency. This is the power efficiency. Of course, the power efficiency, you want to operate your engine as high temperature as possible. The thermal efficiency, as you operate the higher temperature, radiation loss increase. So you have a maximum here. So this is the maximum efficiency you can get about 85% of efficiency out of this. And this happens around 2,450 Kelvin when you have [INAUDIBLE].

And what's interesting is that, actually, there is a pretty wide range. The efficiency, this is actually really good, pretty flat, relatively flat. And so, if you operate, if you think about here, it's only about 1,000 degree. Here is the 4,000 degree. And this is a 7%. Pretty good if you can get there.

And we know the solar-- the coal plant is only 40%. The combined, that's the coal burning plant. Coal plant is about 40%. And if you combine gas turbines, [? and a ?] combined cycle, combined gas turbine with a steam turbine. So you burn fuel, so you generate hot gas, and gas profile turbine, say, a gas turbine and exhaust generate steam. Steam drive a steam turbine. That combined about 60%. That's the best you can do with the fuels.

And an internal combustion engine, the car is about 25% to 30%. So that's the-- so this is a pretty optimistic value here. So if you put your solar-- if you put your thermal engine between the using the heat from the sun. But of course, there are many limitations.

Now, the next question I want to ask is, if I put the material here, under the sun, how far they can get? What's the maximum temperature you can get? And I could imagine a case where you could potentially get to a very high temperature. And this is the-- radiation comes in, you will be up [INAUDIBLE]. I don't think about the direction. Let me just say all direction the same. And again, this is, because of that, maybe you have ways to do better, I don't know yet.

So radiation comes in. These absorptivity of the surface is a function of lambda wavelengths. And then, also, the emission, you will re-radiate. So absorption, if I put the [? rationale, ?] I know the Kirchhoff's law tells me, absorption equals emission for wavelengths at least. At least if I say the rationale one is the same. So it's all diffuse, you can imagine that.

So when I do this, I will have the absorbed energy, this is the-- you can see, this is the spectrum from the sun, and the times absorptivity. [INAUDIBLE] I have integrated the [INAUDIBLE] angle and integrated over d lambda. So that's all the energy comes in. And then, this is the energy that is re-radiated. One is the surface radiation.

In [INAUDIBLE] times blackbody emission, this blackbody emission [INAUDIBLE]. But also the ambient is [INAUDIBLE]. So you have a [INAUDIBLE] change between here and the ambient. So this is the radiation to the ambient. t should not be t, a, t0, ta. And here I have concentration.

As I said, this may not be-- I think this probably is not the maximum. Well, as I talk, I'm just making comments. Because the radiation from the sun is in a very small angle. It's almost lower-- you say lower incidence. And when I write this emission, I am writing the emissivity isotropic. I could potentially design a surface emission only also in the same angle where the sun has. Then I have to do angular integration. That probably will go even higher temperature than this if I just make that guess.

So once the-- in terms of how I-- the spectral characteristics. So if you look at, this is the radiation from the sun. And this might be the radiation emission from [INAUDIBLE] the surface. And at each wavelength, so you can design your selective surface. Ideally, you can design [INAUDIBLE] if you could. Seriously, [? no, ?] seriously, you [? cannot. ?] But it's hard to do.

But let's just say, imagine I have that [INAUDIBLE] surface that I have a sharp cutoff. So below certain wavelengths, all the radiation is absorbed. So that could be the solar radiation. And then, beyond that, all radiation is rejected. So that's a spectral idea 1, 0 spectral properties, selective surfaces.

And so, if this selective surface is a 1, 0, and I can look at, if I design the selective wavelengths here, if you look at it, this blackbody from emission reduces rapidly. So if I make my wavelengths here, this radiation, Kirchhoff's law-- and now I have to remind you of Kirchhoff's law. When I see this spectrum, this absorption is 1, I also mean the emission is also 1. I can't violate that.

So this radiation will be going out. This blue in this region will be emitted if I absorb everything from the sun. That's the second law tells me. So if I have-- I check this wavelength. You can say. Now I make the wavelength shorter, there's less emission from the blue curve. So here is almost 0. But there's still a fraction of the solar radiation that comes in absorbed. So I want to do my energy balance and say, what's the maximum temperature I can get just with a flat surface, one [? sun? ?]

So c equal to 1. And I do, rather than do a blackbody spectrum here, I was trying to do this by hand. And then later on I found that I still couldn't solve the equation. So I get [INAUDIBLE] that came into my office. He has a code that you possibly [INAUDIBLE] you'll see later on.

So here is the radiation from the sun. And I say absorption is 1 becomes 0 lambda. So this is 1 times whatever comes from the sun. So view factor from the sun to Earth's surface, the surface area of the sun, blackbody emission of the sun, t lambda, that's what comes to the Earth's surface. And this is the emission radiation out from the surface. So assuming this surface is facing the sun directly, there's no angle [INAUDIBLE], and emission out and the emission to the ambient, [INAUDIBLE] ambient.

And of course, let's say, I've used this trick before. This area times view factor is the same area on Earth times the view factor from Earth to the sun so that I can cancel the area. So it's the independent of area here. I can cancel the area. And that's why I was doing the universal blackbody curve.

So if I do my universal blackbody curve, this is the radiation between the sun temperature-- I mean, wavelengths normalized to sun 10 to the fourth power. This is the function I want to find the time temperature. I thought I could do this by hand. Again, this function is not [INAUDIBLE]. I can't-- you have to do a [INAUDIBLE] to solve for the [INAUDIBLE].

So but this is definitely solvable. You can go to solve the equation. You can even take the real spectrum to solve it rather than doing blackbody spectrum as I'm doing here. I've written down, in fact, that's what [? King ?] has done. This is the curve a m 0 condition.

And if you choose your wavelengths, it's interesting that the shorter the wavelengths you choose, the higher the temperature you get. That's because the loss is smaller. You look at it, you go to shift to small wavelengths, you absorb the radiation, but you lose very small. Because this curve, once you go to very short, this curve is always below the blackbody curve of the re-emission.

And so you-- but see, isn't this amazing if you have that surface here?

AUDIENCE: My old house, I think I bought my [INAUDIBLE] something.

GANG CHEN: [INAUDIBLE]

AUDIENCE: No, it's black. [INAUDIBLE]. Yeah, no conservation, and no, let's say, no optical treatment, no filters.

GANG CHEN: Right.

AUDIENCE: It's definitely not 600 Kelvin.

GANG CHEN: No, no.

AUDIENCE: It's 81 Celsius.

GANG CHEN: Yes, what is that, is it a flat panel?

AUDIENCE: Yeah.

GANG CHEN: Flat panel? Yeah, flat panel, you got a lot of losses. Firstly, the surface is not bad. The [INAUDIBLE] industry has done a pretty good job. And you can buy-- I visit-- this is the part of the things I'm going to talk later. You can buy commercial this hot water surfaces, have a 95% absorption, 5% emission, not a [? shock ?] [? product. ?] We'll have an example later on.

And another flat panel, it's not a vacuum. You take a vacuum tube that the channel use, you put it inside, you go to 200 degrees Celsius. That's when you don't have water inside it, just dry in [INAUDIBLE].

Yeah, so this is the-- I guess the point is, if you can design, in here is-- if you recall, for thermal engine, 85% efficiency range, or 70 to 85, you need 1,000 to 4,000 temperature range, theoretically. And here, it doesn't seem to be that hard if you've got that surface. Of course, that's a really ideal surface. If you can get it to the 1,000 degree, even with one sun, [? flat-- ?] sorry. And here is another example. [? In ?] 1.5, that's the [INAUDIBLE] Earth. And again, [INAUDIBLE].

Now, for those ideal situation, you can do almost-- this doesn't give you any power. What we did is just to say, it's something equal to the loss, no power. So now let's look at the more realistic case where this is still-- the surface is ideal. But I don't optimize the temperature, trying to reach maximum temperature. I try to say, given a temperature of [? operation, ?] what's the-- I choose the wavelength.

So the way I choose the wavelength, if I say, this is the curve here, then what radiation come in from the sun? And at this wavelength, the blackbody, at this temperature, the blackbody intersect the solar radiation at this temperature, at this wavelength. So I cut out this point. And then, below this wavelength I have 1 above, I have 0.

So the difference from the previous discussion is, previously I say that each wavelength what's the maximum temperature? And here is, I gave a temperature, I choose my wavelength. And then I say, if I operate this engine at this temperature, what's the efficiency I can get? And so, this is the, again, the same picture here other than any of this [INAUDIBLE] and the blackbody, two blackbody working together, I'd say I'm looking at the one sun [INAUDIBLE]. Again, like what I said.

Now, in this case, the thermal efficiency is what comes in at the total, and then this part is lost. The blue curve part is lost. So if I calculate the thermal efficiency, and this is the [INAUDIBLE] mechanics calculation. And as you-- here is the thermal efficiency. So the loss, this is a larger-- the blue-- the purple area is the-- or dark area, this is a 0.9 [? high ?] thermal efficiency.

So naturally, if you want to have a good thermal efficiency, if you want to [INAUDIBLE] out [INAUDIBLE]. So you want to operate, again, at a low temperature. You go the low temperature, [INAUDIBLE]. So that's the-- but of course, you get a 0 power efficiency. So you still got the more optimum. So you multiply this to the power efficiency, and this is the transition wavelengths are here.

And so, this is the-- in this case, what you have is 0.5. So still pretty ideal, pretty good, very good if you can get even half of that. Because 50%, let's assume you have a thermal engine, a power engine operating between, in this case, let's say, here is a 50%, it's a power engine operating between 800 Kelvin to room temperature. And of course, if you have a real efficiency, [INAUDIBLE] that's the power of-- so most likely you're shifted to lower temperature.

This is actually a real selective surface. With selective surfaces from [? sun ?] [? select, ?] this is the emissivity, the absorber in the solar region, and in the IR region. Problem is, nobody could make this really sharp I think. And it's a transition. There are always a transition, the sharper, the better.

And so, if you use this surface to do the calculation, real surface to do calculation, and then, again, assuming a [? power ?] efficiency. So here is the system efficiency now becomes about 30%. And the operator, you don't want to operate at high temperature. You can see here, the [? upper ?] one is actually pretty low temperature, except that you need a device converter that work by the power efficiency here.

If you recall, the solar cell, [INAUDIBLE] sharpening [INAUDIBLE] paper, [INAUDIBLE] limit for single junction solar cell, silicon solar cell, the maximum efficiency is about 28%. Now look at this. Yeah, this is very good. And of course, solar cell is also all thermal energy. It is limited by this efficiency, power efficiency of whatever limit that we're discussing here. Except that the emission [INAUDIBLE]. So not this one, I'm sorry. The emission, solar cell do not have a re-emission problem.

So it's a matter of the what's above the bandgap times the-- the current efficiency limit of solar cell is the solar cell is itself operating at low temperature. So the current efficiency limit is really from the sun temperature as an [INAUDIBLE]. And if you do-- it turns out that if you do infinite multi-junction solar cell, the maximum efficiency is still that 85%, same upper limit.

So those were-- the previous discussion were done for the concentration in first one, one [? sun ?] condition. And you can add other concentrations and the-- use various kind of absorbers. And this is the-- we have a blackbody absorber, these different [? conservation ?] [INAUDIBLE] [? concentration. ?] And that's the temperature of operation here is the efficiency. And now you use a more realistic absorber. The blackbody is [INAUDIBLE] overall spectrum.

Let's say here is a selective absorber. Let's say you get the higher efficiency. And if you compare these two, you also operate at higher temperature. So here you got to operate at a higher temperature. If you selectivity do it, you can push to a higher temperature. If your selectivity is not good, spectrum is not good, then the blackbody, you don't want to operate at high temperature. You want to operate the low temperature because you're losing too much heat.

So the solar thermal energy is always the fight between the losing heat by radiation and the [INAUDIBLE], the thermal energy you want to operate at higher temperature, your surface you want to operate at higher temperature, so optimum there. And now, if you go back to the ideal absorber, ideal absorber means 1 and 0 selectivity spectrum, you push to higher and higher temperature depends on your concentration ratio.

So those were generally [INAUDIBLE] I think the messages. If you can do good spectral control, you can get the high [INAUDIBLE]. So that's to say, spectral control is really a critical problem. And we're [? finding ?] out, doing Department of Energy Research Center, we have two parts. One is we look at the, for example, [INAUDIBLE]. The other is really look at the spectral control.

And in fact, later on, we talk more to thermal [INAUDIBLE]. And you realize that you're transforming one difficulty into another difficulty. In solar cell, the difficulty is the single-junction cell is limited to sharp [INAUDIBLE]. So you try to do multi-junction cell, which people have reached about 41% three-junction. But say, infinite junction you can get to 85%. So but the growing material to more than three junction is very difficult.

And now we transform one problem into one-- this difficulty into another difficulty. If I can have a selective surface, really ideal, that work at a high temperature, then I can [INAUDIBLE] get high efficiency, even with single junctions.

So but of course, this has now a lot of engineering aspects. Because let's suppose, when I have this ideal surface, selective surface of absorptivity, emissivity, on the other side, that you can probably design a surface of really 0 emissions. So this side I will lose radiation.

And also, you have to hold it somehow, 1,000 degree, 2,000 degree, you have to hold it. And of course, you can use, let's say, a suspension. You can use this thing called-- this is actually, if you do the solar in that, this is the one, and the one that I consider solar. If you do with a combustion chamber, it has to [? gas ?] contact [INAUDIBLE] or a very sturdy structure.

At least in the case of the sun, what comes in, let's suppose this is a vacuum chamber. What comes in, then it goes-- photon can go through the glass. Today you have much less in terms of the complexity in dealing with the [? top ?] gas, the physical contact. I think you can use a really-- say, very small [? stream ?] to suspend your surface. So that's one advantage, that [? view, ?] which is probably better, they do the solar compared to thermal source.

So here is the suspension. And of course, if you have suspension, then you have heat loss. You have to account for other heat loss, suspension, and other emission losses. And so it's a, say, then becomes a careful engineering problem. That's why at the end, now even you work on the [INAUDIBLE] thermophotovoltaic, you have to go back to basics on how the conduction, [? key ?] leakage through-- any [? key ?] leakage [INAUDIBLE].

--degree making factor for your system applications. Any questions?