Text-Alternative Version: A Technical Discussion of TM-30-15

Hi. Welcome everyone. I'm Michael Royer with Pacific Northwest National Laboratory, and I'd like to welcome you to today's webinar-- A Technical Discussion of TM-30-15, Why and How it Advances Color Rendition Metrics.

Brought to you by the US Department of Energy Solid-State Lighting Program and the Illuminating Engineering Society.

All right. I'll now introduce the speakers. As I said, I'm Michael Royer, lighting engineer at Pacific Northwest National Lab where for the past four years, I have worked on US Department of Energy Solid-State Lighting Program generally with the focus on technology development issues helping improve product performance through research, testing and standards development.

I'm a member of IES color committee and the chair of the IES color metrics task group that really did the development on TM-30.

So my co-presenters today-- the first, Lorne Whitehead is a professor in the Department of Physics and Astronomy at the University of British Columbia in Vancouver. Throughout his career, he has held leadership roles in the private sector, university research, and administration.

His work has found several university startup companies and widespread technology licenses and lighting and information displays. His research centers on applied optics and has generated over 100 patents. Lorne serves on CIE technical committee 1-90 which is charged with revising the CIE Color Rendering Index, and he is a member of the IES Color Committee.

Also presenting today will be Aurelien David, chief scientist at Soraa. He has researched LED lighting for 13 years. He studied at UC Santa Barbara with Nobel Laureate, Shuji Nakamura, inventor of the blue LED.

His fields of expertise include semiconductor physics, LED efficiency, and color and vision science. He has authored more than 35 journal publications and 20 patents in this field.

So many of you were perhaps on our webinar last week where we discuss some of the understanding and applying issues related to TM-30, and this webinar today will focus on really the technical issues and be a little more mass intensive and really dive into the details of the development of the new metric system and why it's an improvement over existing metrics.

First however, I'd like to-- sorry here-- going a little bit too far-- recap a little bit of the last webinar for some of you who might not have been there just to highlight the topics that were discussed there and what you might not hear during the webinar today.

So we talked last week about the development process and the history that led up to TM-30 over 25 years of committee work and how TM-30 really synthesizes that information to a common comprehensive system.

It addresses both philosophical and technical limitations of CRI to help specifiers determine the most suitable source for an application, help manufacturers differentiate their products.

Development of design guidance in the establishment of specification criteria is an ongoing process.

The document and tools are available at this point. So we encourage everyone to use them and provide feedback and really help drive this towards an industry consensus.

So with that, I'm going to turn it over to Lorne who's going to provide a bit of an introduction, sort of background, on color perception.

Thanks very much, Michael. And good morning everyone. Yes, this is just a brief introductory discussion on perception of colors in objects.

What do we mean by that? Well, here's a photograph of some objects that we are familiar with, and we're used to looking at their appearance under-- in many cases-- under natural light, which most people think that kind of shows the true color. And people differ in their opinions, but most agree that it's desirable for natural objects to be able to be seen approximately correctly so we can judge things from them.

So picture this. We've all had this experience at probably one point or another. You go to a store, you buy a light bulb, you bring it home, you put it on, and you discover when you do that, that the color suddenly changes. Either it becomes very dim or very bright or changes in some other way.

Now normally, the changes are not as extreme as I've shown here, but they matter. I'll show you here some subtle examples of change. On the left, we have that original photograph with a high color rendering illuminate. And now on the right, it's shown under a CRI 80 lamp, and it's not dramatically different. But it's different.

You'll notice that the purple flower on the left looks blue on the right. The red tomatoes look less red under the CRI 80 lamp. And of course, various CRI 80 lamps could cause various kinds of color shifts.

So we'd like to understand this and deal with it intelligently. In a broad sense, the question is, is this acceptable error?

But of course, that depends on the consumer. It depends on the user. It depends on the setting, the task, many things. So it's a complicated question, but it's one that we would like to be able to answer well. And at the moment I think as we'll hear later on, the CRI has had some difficulties doing that.

So we'll be studying that. But in order to do so, we need to think a little bit more carefully about what's actually going on when we perceive color. So I'm now going to state the obvious, but it's just an introductory idea to get us going.

You don't see color if you don't have light. So the start of the story is a light source, and of course, we quantify the nature of that source by quantifying its spectral power distribution, or SPD.

The light from that source lands on an object. In this case, it's a strawberry. It's shown in monochrome because color doesn't reside in objects. What is in the physical world is a variation of spectral reflectance as a function of wavelength, shown here with the strawberry where the reflectance is increasing toward the longer wavelength end of the visible spectrum.

There's no color here. What does happen here, the SPD of the incident light interacts with the reflectance function of the object. To produce reflected light, it has its own unique spectral power distribution, which is kind of the product of the two precursors.

Again, there's no color here, but there is reflected light. In this case, it has a predominance of energy at the longer wavelength end of the spectrum.

Now the magic happens. The light enters the human eye-- I'm sorry. There's a glitch in this. Apologize. It won't happen again. I don't know why that happened.

But anyway, when we get to this point where the light enters the human eye, we get the beginning of the phenomenon of color.

What happens here is there are three photoreceptors in the eye. Most of us know this. The first has a peak in the short wavelengths end of the spectrum, and then there's one sort of toward the middle far right and one a little bit further to the right. That's the long wavelength end of the spectrum.

And here's the key thing-- when those photo receptors interact with the spectral power distribution of the light coming from the object, they react differently based on what that distribution is. In a very real sense, the ratio of the intensity of the signal coming from each of the three photoreceptors tells us a great deal about what's going on in the reflected light spectrum-wise.

Now that deduction of that spectrum-wise information happens in the retina. Actually there's processing in the human retina. And then further along, there's processing that occurs after the information has been transmitted to the brain, finally yielding the color sensation in our conscious perception.

Now the key thing is that color sensation is representative, tells us something, about the nature of the object. And that's one of the reasons that color is important.

So let's go back to the object, and talk about the object spectral reflectance just a little bit more.

So here we have a graph, in this case, showing the spectral reflectance function of two objects, a green apple and a red strawberry. They're different. They're also different color.

So the fact that the apple is green and the strawberry is red in our perception tells us useful things about the information. Actually in the case of the strawberry, it's useful chemical information. And interestingly, it's molecules in the surfaces of objects that create these spectral reflectance patterns and therefore our color perception, which tells us about those patterns, tells us about what's in them.

In the case of the strawberry, if the strawberry is red, it will be sweet. It will be more nourishing. That's useful information. Actually sugar doesn't have color, but there are molecules in the strawberry that correlate with sugar which do. So it's a useful clue.

And most experts believe color vision is extremely important to people today because in our evolutionary upbringing, accurate perception of color was important to survival. Anyway, people say they like accurate color.

So that brings up an interesting question. When people say they like something, that's a matter of opinion. And there are interesting debates about to what extent we can talk concretely about something that is only in the human mind, color.

The answer is kind of good news. It turns out that the spectral sensitivity functions of the three cones in the human eyes are pretty much the same-- very similar-- for people of normal color vision. And the net result is there are some really good commonalities in the world of color.

The biggest one is that if two people of normal color vision look at two objects and the first person says those objects are similar in color, the second person will agree almost always. And in fact, because we understand the mathematics and physiology of human vision, we are able to predict that agreement as well.

But at any rate, the key point here is that there is a substantial amount of agreement, and that makes it possible to organize colors in various schemes. Here's an example here.

Interestingly, there is no one-dimensional way of organizing colors in a meaningful way where proximity equals similar color. There's no two-dimensional way. But in three dimensions, it's possible. And that number three corresponds to the number of human photoreceptors.

If we had four, we'd have to go in the fourth dimension. But fortunately that's not necessary.

So there are many classification, or organizational, schemes for color that have this appearance. They're 3-D, and almost all of them have the common characteristic that the vertical direction represents what is often called lightness, how close the color is to white rather than black basically. Lighter colors are up, higher.

And in the radial direction, we usually use the term saturation, or chroma, to discuss the extent to which a color differs from gray, the shade of gray. So as you go to the outside of the diagram, as you can clearly see, the colors become more intense. They have higher saturation, or chroma.

And then the third dimension, often represented in the circumferential path is called hue, and sometimes it's defined as the relative degree of redness, blueness, greenness, or yellowness. Some don't like that definition. It sounds like it's a circular, but the good thing is people agree on hue.

And actually we understand hue in terms of what's going on in the human retina and in the brain. We can predict it.

So the good news is there are very good schemes for describing color, and we'll need to use those in the ensuing discussions.

The other thing we'll need to do is talk about the effect of the light source on color. So picture this. We have a reference illuminant that we agree is good color, and under it, we've got a bunch of color samples. This is actually the Munsell set of colors.

And then we change the illuminant. So maybe beside it we put another illuminant. And underneath that test source, we put the same exact color scheme, and they look different.

So you might want to try to describe how they look different and to be quantitative about it. Well, one way that you could absolutely do that would be to take a look at each of the colors on the right-- each of the color chips on the right-- and look to the left to see where it matches.

So this is an example of that color match here, and you could quantify it-- the shift in hue, the shift in chroma, and the shift in lightness. Very easy to do that.

So we can do that using physical samples, but we also can do it mathematically. We know how. We'll be discussing that later today.

Here's the problem. There are millions of samples. And actually for every individual color shown in this diagram, there could be thousands of different spectral reflectance functions that produce that same color. So the amount of information about color shifts is huge. And remember, each shift is three shifts in three different dimensions.

So what do you do with that information? That is the key challenge.

So our goal is to have a useful way to summarize that information that helps us do what we need to do.

So what do we need to do? Well, we need to calculate that metric, whatever it could be. We have to be able to communicate it effectively with one another. We have to use that information to specify desirable, or what we expect to be acceptable, lighting conditions. And manufacturers and installers need to be able to achieve it.

So our goal with IES TM-30 is to help with that process, and that's the purpose of the remainder of this talk.

With that, Michael back over to you.

So just a brief overview of the topics we'll be covering today. I'll be providing a review of the CRI-- a little bit different from what we discussed last week. We'll then talk about the use of up-to-date color space in calculations. We'll take some brief questions at that point.

Then we'll move on to the development of the color evaluation samples. A lot of questions about this last week as well as the reference illuminants that are used in calculations. Again, another quick break for questions. And the final segment will be on the calculation procedure and outputs.

Another reminder-- there is the other webinars that we had last week, and that's available at the link provided there.

OK. So 1: A Brief Review of CIE CRI.

So the basic flow chart of how to calculate this is actually common to TM-30. So what we're doing first is determining the CCT of the test source, the source you're considering. We're determining a reference source at the same CCT.

We then calculate the chromaticity of color samples under the test and reference sources. And then we determine the average difference in chromaticity for the two sets, make a slight mathematical manipulation of that number, and we get our CRI score.

So we'll step through this now sort of in a graphical example. So if we have a test source, say this lamp on the left here-- we're going to pick a reference source that's at the same CCT.

Here, I'm just showing a lamp. It's not a physical lamp. It's actually a mathematical thing. Just an image there because I need an image to compare it with for you.

So what we're really comparing here, as Lorne illustrated, is the spectral power distribution emitted by these lamps. So we have this mathematical equation that we're dealing with. We have one for the test source and one for the reference source.

Now we also have our color samples. In this case, here are the eight pastel colors sample shown for the calculation Ra, which is the average value that is produced by CRI.

We also have in the CRI system, six additional samples which are more saturated, which provide special color rendering indices, for example, R9, which you might be familiar.

And again, we're not actually shining any lights on these samples. Physical samples don't actually exist for these colors anymore today. They're not available for purchase is what I mean to say.

What we're doing mathematically is using the reflectance functions of the samples. We have the interaction of the spectral power distribution and the spectral reflectance function to compare numerically these eight color samples.

So we calculate the chromaticity for each of those samples under the test and reference condition, and then we determine the difference between each of those chromaticities before we scale that value and subtract it from 100 to get the score for each individual sample. And finally, we average those eight scores to get the Ra or the CRI as it's commonly referred to.

So if we compare this what we're doing with CRI to TM-30 and what we're going to talk about today, with CRI, we're using the CIE 1964 chromaticity diagram U\*V\*W\* .

Now, if you think about the world in the 1960s, it's a little bit different than it is today. Science has advanced a lot in that time. So now we're-- in TM-30-- using the CAMO2-UCS which is built on the CIECAMO2 color appearance model.

With CRI, we had the eight color samples of medium chroma and lightness with varying spectral sensitivity because they are only made up of Munsell samples which only use a limited number of dyes.

In contrast with TM-30, we have 99 color samples, we have uniform color space coverage, neutral spectral sensitivity, and a variety of real objects that include things like skin tones, plants, paints, inks, textiles, all kind of real objects.

We discussed a lot last week CRI's only a fidelity metric, but with TM-30, we have a fidelity metric on average, an average gamma metric, graphical representations, and lots of detailed values to provide a hierarchy of information. It really suits the needs of different levels of users.

In CRI, we have a step function in the reference illuminant where in TM-30, we've made a continuous blend between the illuminants. We're using the same reference illuminants of blending over a range which is particularly important for, say color tuning products, where you wouldn't want a sudden change in the score just because it transitioned across an artificial threshold.

So these are all the things on the right side of the screen that we're going to be covering today.

Now, just another brief overview, CRI-- it's a color fidelity metric. It doesn't tell us anything about change in saturation, color preference, color discrimination, hue-specific changes, no graphical results.

So we've added all those things to address the philosophical limitations. Another example-- we have one reference condition on the left here. We have an equal amount of change to test condition one and test condition two. But with CRI, we have no way of distinguishing that difference. So it's a very different visual experience, but it would be rated the same.

So finally, we have TM-30. This is an outline-- a repeat of a slide from last week. The core calculation, the modern color science, and new color samples. That today will be the focus of the initial sections, and then we'll be covering the different outputs that are shown on the right side of the screen towards the end of the presentation today.

So with that, I'm going to turn it over, and we'll go to Part 2: The Use of Up-to-date Color Space.

Thanks very much, Michael. This'll be a relatively brief introduction to this idea, and it's an idea most of us are very familiar with in one particular way. I think there's nobody that hasn't seen the CIE xy chromaticity diagram, and it is a useful method for discussing the color appearance of lamps-- of light sources. It's a two-dimensional plot. It makes it simple to put things on a piece of paper and compare them.

We're not going to discuss it much. In fact, the key thing that I'd like to say is that this is actually not in any way a useful color space for describing 3D object color. It has almost nothing to do with color. And yet, we find often people try to grapple with the ideas of color space for objects by trying to compress it into this space. It just doesn't work. They're completely different ideas.

So our polite request for today with regard to the xy chromaticity diagram is please try to forget about it. We're going to go on and deal entirely with three-dimensional color spaces.

Now, there are many. As I mentioned at the very beginning introduction, there are many ways of doing this. I find often the Munsell system is generally the most familiar. Although, almost everybody has a favorite preferred other system, but they all have very similar characteristics. And that is, as mentioned earlier, that they treat proximity well.

Colors are placed in a way that seems sensible to human perception. In the case of Munsell, that was the only priority really was to get a sensible display from the point of view of discerning viewers of color. But there is a problem. The problem is that what we need to do in color rendering, both originally with the CRI and now with IES TM-30, is to calculate color shifts.

And the information we have available for that is the spectral power distribution of the source and the spectral reflectance function of the object. And there isn't actually a straight way to use, for example, the Munsell system from that perspective. It's not impossible, but it's not straightforward.

So our goal is to solve that to have a way of-- in a straightforward way-- getting useful color coordinates from the mathematical information that we have at hand. And we have chosen CAMO2-UCS as the tool for doing that calculation. It's the best so far. And as I've said, it eats, it takes its input, the spectral power distribution of the source and the sample spectral reflectance function, and it calculates the three components of object color. So those three components are-- in this case, they're called j prime, a prime, b prime.

They're in the three dimensions of space, and actually although they're Cartesian coordinates, they describe very, very similarly to the way the Munsell system describes color. And it works mathematically.

The one thing I'll acknowledge is that the formulas in CAMO2-UCS look kind of ugly. There's quite complex polynomial functions that calculate the right answers, but they work really well. And they're very practical for calculation. So they're the perfect tool for this job.

And on that note, I'll hand over to Aurelien.

Yeah. Thank you, Lorne.

So I would like to say a few more things about what we like in CAMO2-UCS and give you more details on this color space.

So as Lorne mentioned, the math behind this color space is pretty heavy, and we're not going to tell you about the math today. Rather we'll show you some nice properties that we like in CAMO2-UCS.

So these graphs should give you an idea of what colors look like when they are sorted in CAMO2-UCS. The plot on the left is what we call the color volume. So this is the ensemble of all possible colors that our vision system can perceive. And you see that things look very similar to the Munsell system that Lorne showed a bit earlier.

We have a vertical axis which tells us about lightness, and then we have a change in hue and saturation in the 2D ab plane.

And the one thing that you notice which is nice is the shape of the color volume is fairly regular. It's kind of a bowl shape, which is kind of a natural simple shape, and you can contrast that for instance to the weird shape of the xy color diagram, which has a horseshoe kind of shape. So CAMO2-UCS has this kind of clean bowl shape which we like.

The plot on the right gives you an idea of what happens if we cut slices through this volume. And so you see different slices with different lightness.

So again, this regular shape is something that intuitively we like, but more importantly, what we like is that the shape of the color space does not really change when we change the color temperature of a light source.

To illustrate this, this slide shows you what happens when we take a slice across the color volume in CAMO2-UCS. And we compute this cross-section at two different color temperatures.

So we take 3,000 Kelvin blackbody and a 5,000 Kelvin blackbody, and we compute the color volume. And you see that the shape hardly changes. What this tells you is the colors computed at 3,000 and 5,000 Kelvins are about to same. And we know that in practice this is true.

We know that when we look at the color of an object and there are 3,000 or 5,000 Kelvin blackbodies, we perceive the colors of objects as being essentially similar. So of course, it's a property that is true in human vision, and it is a good thing that CAMO2-UCS is mimicking this property of color constancy.

I want to show you that this is not a trivial property. And so to show that, I'm going to contrast CAMO2-UCS with another color space, and that is UVW, which is the color space used in the CIE CRI calculation.

So the plots on the right show the same calculation as on the left where we take a slice through the color space at four different color temperatures, 3,000 to 6,000 Kelvin.

Now, the red dots show you what happens when we do these calculations in CAMO2-UCS, and essentially the information is the same as what we saw on the left part of the slide. We see that we have this bowl shape that really doesn't change as we change the color temperature.

In contrast to that, you see that in UVW things are not nearly as nice. So the black dots in this plot show the shape of the color space, or this cross-section of the color space in UVW. And you can see that this shape is now very elongated. And more problematically, this shape changes with CCT.

So that tells us that there is some inaccuracy in UVW which is going to change with color temperature. So UVW is not able to represent the fact that colors are constant across CCTs in our main system.

So again CAMO2-UCS does this properly and this is a thing we want.

I'd like to mention another important property-- OK. Sorry. This is one additional slide which shows you yet another example of a color space where things don't happen so well.

So this is CIELAB. CIELAB is a fairly popular color space. It's kind of a simpler version of CAMO2-UCS. It's much less sophisticated. And you see that in CIELAB, again, the shape of the color space is changing with CCT, which is something we do not want.

So that being said, I'd like to switch to another important property of CAMO2-UCS, which is color uniformity. When we talk about the color rendering of a light source, we want to be able to compare color distortions. What I mean is we want to say under this light source, red colors are very well rendering, but green colors are being distorted. This is a kind of information we want to convey.

And of course, in order for us to be able to do that, we need a calculation tool where we can compare the rendering of green, blue, and red colors. And essentially this property is what is called color uniformity.

To be able to do that, you need a color space where you can compare color distortions for different colors. And this very important property unfortunately is very hard to achieve in practice.

So to illustrate this, I'm showing you a fairly well known image which is the shape of the MacAdam ellipses in the xy diagram.

So the MacAdam ellipses correspond to color differences which are perceived by us as being roughly equivalent. So you have the red color shift, the green color shift, and so on. And we perceive them as being of similar magnitudes.

And so you would like to see that in a given color space they appear as being of equal magnitude. And you see that in the xy diagram this is not the case. So the shape of these ellipses is very elongated and it depends a lot on the area of the color diagram.

So this plot shows you that in the xy color space, green errors, or green color differences, are going to be relatively exaggerated whereas blue purple color differences are going to be underevaluated.

So this is a great counter example of a color space where you would not want to be running a color rendition calculation.

In contrast, this is equivalent data in CAMO2-UCS, and you can appreciate on this plot that the ellipses are now much better behaved. They look more circular. They are not as elongated, and the relative size of the ellipses is quite similar across color space. So this is an indication that CAMO2-UCS is a uniform color space that is a color space where we can compare color distortions for red, green, yellow, and blue in an accurate way.

And one last way to illustrate this is to contrast CAMO2-UCS again with the CIELAB color space. And you see that CIELAB is not nearly as nice as CAMO2-UCS. Here the color distortion ellipses are much more elongated and they changed appreciably in shape across the color space.

So I think this wraps up some of the essential properties of CAMO2-UCS which we like and which motivated us in selecting this color space for TM-30. And it appears now is time--

All right. Thanks, Aurelien. We got a few questions in so far. Not very many. One of the questions I'll just answer quickly-- when will the Excel workbook be available? That is available now. If you've purchased the TM, you'll find the link in the document that will take you to where you can download the Excel file.

I think most of these we're going to answer again coming up later in the presentation.

Let's see. There's a couple questions about color temperature I guess we can just touch on briefly. This isn't directly related, but we'll answer these.

One is-- do we still use color temperature, Kelvin temperature?

And another is-- once a new metric for color rendering is adopted, will that lead to a new CCT metric that is more descriptive for LED sources?

Aurelien or Lorne do you want to answer those?

I think, Aurelien, that's probably a better question for you since you're in the LED industry.

Right. So, first, are we still using Kelvin? Yes, absolutely right. In TM-30 we are not proposing any significant changes to the way color temperature is being computed.

And I think this is a kind of a practical choice we made. There is, I think, awareness in the color science community that color temperature is not a very creative concept, meaning it doesn't necessarily correlate very well with our perception.

However, it's still a useful tool to be able to run calculations, and I think we agree that reforming color temperature would be a fairly substantial task which would probably take and effort in its own right.

So because of that, there has been a decision to not question the notation of CCT. We don't see it as a big problem in that it doesn't degrade the accuracy of the predictions of TM-30, but we are left with the common limitation of color temperature which is that it's not very well correlated with human perception.

Lorne, did you want to add any comments to this?

No. I fully agree. And when you say it's not very correlated, Aurelien, I think what you really are saying is that the variation of the apparent color of the source as a function of color temperature isn't necessarily matching human perception. So there could be a scale that would be more related to human perception of color. It would just be a different scale, but it wouldn't change the idea that the blackbody changes color as its actual temperature changes.

Right.

I'll add one final thing to that too. I think one thing that's helped is the addition of Duv to correlated color temperature. So if we think of chromaticity, a color of light source as Lorne showed in the color space, it's really a two-dimensional plot. And CCT is trying to distill that into a single number.

You can't really show two dimensions with a single number. So there's some limitations that arise. Now if we pair that CCT number with a second number, now we have another two-dimensional system that can do a more effective job of characterizing the color appearance of light sources-- again, not objects, but of light sources themselves. So we can tell how pink or green is a source along with how blue or yellow it might be.

So I think most of these other questions refer to the color samples which is the section that's coming up next. So with that, I think we'll just continue and save some more time for questions towards the end.

OK. So let's keep going then, and I guess I'm going to keep speaking for now.

So let's talk about the test samples. The choice of the test samples was a big deal in TM-30. It was a big chunk of the work. And historically speaking, choosing the test samples in a color rendition metric has always been a contentious and difficult issue, and that is because different people have very different opinions on what matters and the properties that the test sample should have.

So as we all know, the CRI has eight test samples. More modern color rendition metrics have suggested increasing the number of samples essentially to improve accuracy.

This slide shows you a short laundry list of the properties we considered desirable when we established the test samples of TM-30.

So first, we decided it would only use real samples. So we are only using reflectance data from samples that have been measured in the real world. Moreover, we are taking data from a wide variety of objects both man-made and natural objects with different types of materials.

We also wanted to make sure that we were including a wide variety of colors, including unsaturated as well as saturated samples. And we took great care to make sure that there was no bias in our reflectance data. This is what we call wavelength uniformity, and we will discuss this in more details in a few slides.

Finally, there's always a question of how many samples are suitable for the calculation. And so we tried to optimize the sample count to have enough samples to be highly accurate but as few as possible to make the calculation practical.

So with these general prescriptions in mind, I would like to get in more detail the sample sets.

So first, let me remind you about the eight samples of the CRI. And as we know, these samples tend to be fairly unsaturated. So this plot illustrates this by cutting the color coordinates of these eight test samples in CAMO2-UCS.

And you see that all eight examples are fairly close to the origin of this space, which tells us they're not very saturated. And there is some complaint about that. People worry that because we don't have saturated examples we're not necessarily predicting what happens to saturated colors which we care about.

All right. So let's move on to how we did the job in TM-30. So the first thing we did was we gathered a large amount of reflectance data from various sources, and we ended up with a database of more than 100,000 reflectance samples from a variety of objects man-made and natural.

So this plot illustrates our collection. So again, this is a cross-section of the color space in CAMO2-UCS. The colored boundary shows you the limit of the color space-- so theoretically possible color. And the gray shape shows you the gamut of the samples we have gathered in this work. So the 100,000 samples we gathered cover this gray patch, and you see it's a very wide gamut. It goes pretty close to the edge of the color space.

That being said, the next thing we did was to actually restrict the sample set by removing some of the samples to end up with this blue shape. So we established what we call a gamut of common colors, and you see that we dropped some of the samples that were in the gray belt between the blue boundary and the gray boundary.

Why did we do this? Well, we had two reasons to remove some of the samples. First, if you look at the density of samples inside that gray patch, we find that the samples become sparse near the edge of the gray boundary. So these are regions where we have a little bit of reflectance data, but not very much. And this suggests that these colors are very common, and therefore they're probably not relevant for statistical averaging.

The second argument is the validity of color error formulas. When we run color validity or color rendering calculations, we need to use color difference formulas. And it turns out these formulas have only been tested in a given fraction of the color space. And in regions of very high saturation, color difference formulas have not been tested, and therefore they might be inaccurate.

Now it turns out that the regions of low sample density coincide very well with the regions where the color difference formula has not been tested, which makes sense. Right? These are very uncommon colors, and people haven't really looked at then too much.

And so for these two reasons, we decided to dispatch all these discards, all these samples, where we had no confidence in the color difference formula. And so we only keep samples in the blue patch.

After this procedure, we drop the sample count from about 100,000 to about 60,000.

So this is nice, but inside this blue patch, the samples are still distributed in a very non-uniform way. So some regions in the blue patch will have more samples relatively than others. And we would like to span the blue patch of common colors in a more uniform way.

So as I was saying, we cut small pixels in the color space, and we look at all the reflectance samples inside a given pixel. And we only keep one sample per pixel. So this way, we go from a non-uniform sample distribution to a uniform sample distribution.

So some of these pixels will have a few samples. Others will have many, but we only keep one sample per pixel. So this is what we end up with. We end up with a pixelated map where each pixel in the color space has one and only one reflectance sample.

So another way to illustrate this is if we look back at our cross-section of the color space, we do something like this. We only keep some samples, and we keep them more or less equally spaced from each other.

So at this point, we end up with a nice collection of samples which covers common colors, and it does that in a uniform way. That being said, we still have one task, which is an important task, which is wavelength uniformity.

Lorne, I'll let you say a few words about this.

Thanks very much, Aurelien.

And yes. This next concept is not difficult to describe, but it's difficult to do quickly. And I'm going to take an explanation shortcut here by using an analogy. So if you don't mind, I'd like you to imagine just for a moment that V lambda has a measurement error in it, but no one knew about it.

Now here's the sketch. So this is not V lambda. It's V lambda with a dip in the center. But suppose originally when V lambda was measured, this is what we got because of an error in a laboratory, and nobody knew it what was wrong. So this was the official version of V lambda.

Well, it wouldn't have made a huge difference up until fairly recently because most light sources were fairly broad, and it wouldn't have given a huge error. But of course with the advent of LEDs, it would make a very big difference. What we would expect is that LED manufacturers-- if this was the V lambda they were dealing with-- would very rapidly evolve to SPDs that took advantage of these bumps and dips.

Now if bumps and dips in any response function are real, well, by all means, take advantage of them. But in fact, if they're not real-- if they're errors and spectral information is manipulated to take advantage of those errors, which is sometimes called gaming, this is not good for consumers and it wastes energy.

So this is why in any situation where we have errors causing non-uniformities in measures we can end up-- through nobody's fault-- encouraging or incentivizing manufacturers to do the wrong thing. So we'd very much like to avoid that.

And in fact, it turns out that the CRI has such a problem built into it. It's a subtle problem. It's not a problem with V lambda, but it's a problem that nevertheless causes disuniformity in responses. And that creates errors and wastes energy.

So here's the story. The CRI measure, Ra-- that average error function-- is caused mainly by sharp spectral features. That's the major thing that causes color shifts to occur. And so it makes sense to talk about the sensitivity that the CRI function has to sharp spectral features.

And how that sensitivity in turn depends on where you are in the visible wavelength. So that's a sensible idea to discuss. It just wasn't discussed until recently.

But when we study that, what we would hope to find is that that wavelength dependence of the CRI sensitivity would correspond or arise from just the normal response functions of the human visual system, which varies smoothly with wavelengths. So we would expect a smooth response function.

Of course, no response in the infrared, no response in the UV, response to increases and then decreases again with details all arising from the various, very subtle computation in the visual system. That's what we would hope for.

But in fact, what we find when we look at the CRI metric is that's not the case. It's not smooth. And that non-smoothness creates bumps like in the previous analogy that can be gained.

So I should add that we're not blaming our forefathers in creating the CRI. They never could have understood this in the pre-computer era. It was a very subtle and difficult thing at that time to even understand. Although there have been hints over the years that there was a problem there. It wasn't easy to analyze it, and it was not possible to fix it.

But now, we can do this, and we must do it. And Aurelien will now take over again and discuss how we avoid the possibility of that LED gaming in the future.

Right. So I'd like to give you more illustration of what happens when the sample set used in a calculation suffers from this game ability that Lorne just mentioned.

And in order to convince you that this can indeed be the case, I'm going to start with a very extreme example. I'm going to take three paints-- a blue, a green, and a red paint of pigment-- and I'm going to run a calculation where I mix these paints to create a sample set.

So you see we have a very nice sample set covering a wide range of colors. The colors of these different lines represents the actual sample color. And so we can run a color rendition calculation with this sample set, but you can probably tell that this would be a bad idea. There's something weird with these reflectance samples because of the way they've been built or the variations in reflectance happen at two specific wavelengths-- 500 and 600 nanometers. And of course, that has to do with the paints used to generate these samples.

So intuitively we can expect that this set of reflectance samples are going to be more sensitive-- that's 500 and 600 nanometers-- than at other wavelengths, and we don't want that.

In fact, it's possible to quantify this artifact. We can compute what we call the wavelength sensitivity function, and this is the quantity which tells you which wavelengths matter for a given sample set.

And if we run this calculation for the set of samples I just showed you, this is what we find. So we find that these samples are extremely sensitive at 500 and 600 nanometers, and they're very insensitive at other wavelengths.

Obviously this is a bad thing because this doesn't represent a reality in our vision system. It doesn't represent the reality in objects in the real world. It's just an artifact which is caused by how these specific test samples were generated.

Now, obviously these set of samples-- these RGB sample sets-- is kind of a caricature. I don't think anybody would suggest actually using those for real world calculations. And we would expect that real test samples do much better than this.

Well, in fact, that's not necessarily the case. If we look at the CRI test samples and we run the same calculation, we find a sensitivity function which is still pretty bad in the sense that it still has fairly sizable peaks and valleys.

And so this tells us that just like our RGB sample set, the eight samples of the CRI suffer from the wavelength bias where some wavelengths are going to matter more, and other wavelengths are going to matter less. And that is an artifact.

How is that possible? Well, it turns out in the generation of the 8 TCS, only a few pigments or dyes were used. And so it's essentially the same fundamental reason as the reason of the RGB set.

So now that we recognize this issue, we can try to solve it. And this takes a little bit of math, which I'm going to mention very quickly in this slide.

So, you can convince yourself that what matters for color shapes and color differences is variations in reflectance. And variations in reflectance can be linked to the derivatives of the reflectance function. So r prime would be the first derivative. r second will be the second derivative of sample reflectance. And these quantities are what drive color shapes.

So we can actually write an equation which measures the average bias in a sample set by looking at how the derivatives of reflectance are distributed across wavelengths.

So this is a bit of a heavy equation, but the important thing to know is that this quantity, F, is a measure of the bias of a sample set. Larger values of F correspond to a larger bias, and small values of F correspond to a sample set which is unbiased which treats a wavelength of light equally.

So what we want is the sample set for which F is very close to zero.

Well, now that this tool is defined, we can use it to select our samples. How do we do this?

We go back to the procedure I mentioned a few slides ago where we take the color space and we cut pixels across a color space. And within each pixel, we only select one sample.

But now we do this with care. Each time we select a sample inside a pixel, we select the sample which will make F, our bias function, as small as possible.

And so we do this little by little across all the pixels in the color space in a way which minimizes our figure of [INAUDIBLE], F, and therefore generates a set that doesn't have wavelength bias.

The plot on the right is just an illustration of what happens when we do this. So here, I'm only showing four samples which are being selected by this procedure. And the thing to notice is that variations in reflectance are now occurring all over the wavelength range. So each of these samples has variation features which occurs at different positions.

Of course, this is only for four samples. But as we cycle through the color space and add more and more reflectance samples, we end up with a set where variations in reflectance happen at all wavelengths.

So what's the result of this procedure in terms of the wavelength sensitivity? So again, this is the plot I showed before with the problematic sensitivity of the CRI samples. And in contrast, this is what we obtain with the samples of TM-30.

You see that this function is now much flatter which corresponds to a very low value of this function F. So essentially we've removed the wavelength bias that other samples sets tend to suffer from.

I would like to open a parenthesis here to illustrate how this matters for actual predictions from calculations.

So I'm going to show you results of a color fidelity calculation even though we haven't given you the math or color fidelity yet, but please bear with me.

So on this slide, we are considering a set of SPDs, a set of spectra, which are composed of only three peaks. We have a blue peak, a green peak, and a red peak. And they're very sharp, very narrow. And we varied the red peak. So we generate a series of SPDs where the wavelength of red light is being varied.

And for each of these SPDs we can compute color fidelity as shown on the right. And we run this calculation with two set of samples-- the TCS of the CRI and the TM-30 samples.

And you can see that trends are fairly different. Well, there is an overall trend for improvement in fidelity at longer red wavelengths. But in the case of the TM-30 samples, this is a smooth well behaved variation.

In contrast, you see that with the CRI samples, we have an additional short scale variation on top of this blue curve with peaks and valleys which are caused by the bias in the reflectance of the test samples. So this is an illustration of how having color uniform samples removes the kind of inaccuracy we're worried about.

In terms of magnitude, you see that this can be a very strong effect. In this case, plus minus five to 10 points. Sometimes it's even worse.

Now, this is just one example with a fairly extreme set of spectra, SPDs, but I want to mention that there are many examples where spectral non-uniformity impacts predictions. And one practical example that we run into in everyday life is compact fluorescent lamps.

So there is evidence for my work that compact fluorescent lamps have been optimized taking into account the spectral sensitivity of these CRI samples. And therefore, they tend to be over evaluated because of this artifact. So clearly, this is an issue which is real in our common day experience.

After the discussion of color uniformity, I would like to wrap things up by talking about the number of samples.

So the procedure I described in previous slides can be achieved with any number of samples. And as we know, there is a general trade off between accuracy and simplicity where the more samples we have in general improve accuracy, but we make the calculation heavier.

So we've devised an optimization procedure to minimize the sample set while maintaining accuracy, and these two plots show you an illustration of what happens as you go down in sample count.

So you have fewer samples, but you still cover the same range in color space. And we have been able to devise a set of only 99 samples which retain the accuracy of larger sample sets.

This is the actual reflectance data of the 99 samples used at the end of this process in TM-30. And even though this is a fairly busy slide, you can probably appreciate how these different samples have variations in reflectance that occur at every wavelength in the visible range. So this is an indirect manifestation of the wavelength uniformity.

And finally, these are color patches which show you the perceived colors of these samples.

So this wraps up our discussion of how we generated the sample sets, and I think now is time for questions about these. Or I don't know, Mike. Did you want to take questions later?

We can go ahead and answer a couple questions now, and then we'll continue with a couple more questions after the next section. So I have one that says, with traditional sources, if you were comparing the CRI of two different sources, you had to be at the same CCT. Is that still the case in TM-30?

Lorne or Aurelien?

I'll be happy to answer it, but I just want to make sure I heard you correctly. If two different sources have-- well, maybe you could read it one more time if you wouldn't mind, Michael.

So essentially the guidance with CRI was always that if you're trying to compare two numbers for CRI, you should be doing so for sources that are the same color temperature.

Oh. I see.

Essentially, the meaning of that is that CRI-- and this is the same case with TM-30-- is not predicting the actual appearance of objects. So if you have sources at two different CCTs, one is comparing to one reference, and one is comparing to a different reference. So even though they might have the same score, they're not going to look the same.

Yeah. I understand. I think I understand the question now, and it's a very good one. And I think actually it's a good point with regard to the philosophy of the IES introducing this metric.

This is something we want to hear from people about. We hope this will be much better with this new metric because we're using a better color space for all the reasons that Aurelien had mentioned about the better behavior as color temperature changes.

There's a good chance that there will be much more comparability between measures of color rendering at different color temperatures, but it's not even quite clear how to define that question let alone assess it. So I think this is where we're really hoping for excellent feedback from users of the tool.

Another one, and this-- someone obviously has been reading the TM because this wasn't actually discussed in the presentation, but is there reason why the 10 degree color matching functions are used for calculating RF and RG? Aurelien, do you want to take that one?

Yeah. So, this is a choice we made. I think there is a general agreement in the color science community that the traditional two degree color matching functions are fairly inaccurate, and they tend to make predictions which are not very well correlated to perception.

And in a lot of the studies-- of human factor studies-- we get better agreements with calculations if we use other color matching functions. And the 10 degree 1964 CMFs are more predictive of human perception.

So that's why we made that choice. There are- we should mention-- other more recent color matching functions which are now being approved by the CIE. But because these were not exactly vetted yet at the time of writing this TM, we decided to use the 10 degree CMFs.

So essentially, the answer is we expect we're going to get too much better accuracy in terms of human perception by using 10 degree CMFs.

OK. One final question in this block here. Does this-- and I'm not sure what this refers to-- account for any shifts away from the blackbody i.e. positive or negative Duv values? Is the accuracy limited to color points close to the blackbody?

I suggest we hold on that one because we'll be covering that in just a couple of minutes.

OK. Why don't we go ahead and continue then. I think, Lorne, you're coming up next.

Yes. Thank you. So I'll start by discussing the key point of the choice of reference illuminants for the calculations that we've been discussing.

Briefly, we're not changing them. So the CRI used blackbody radiators and also phases of daylight, and we propose to do the same. And I just wanted to describe why.

So in the case of daylight, starting with that, there doesn't seem to be any issue there. Daylight obviously is universally available. It's a nice smooth spectrum-- not perfectly smooth, but for all practical purposes, it is. And by definition, most agree it produces the truest color. So we're certainly not proposing to change that.

Where things get a little bit more subtle and where you could say there's maybe dispute is on the topic of the use of blackbody radiators as a reference for low CCT. And in fact, some have suggested the only reason the blackbody radiator was selected as the low CCT reference originally was that it was commonly available. And nowadays because we're absolutely not constrained in that regard, perhaps there would be a much better reference.

Well, that's kind of unlikely. And that sort of standard of convenience argument I just mentioned I think is invalid. And here's an analogy to help explain that. Consider the high pressure sodium lamp. It has low color rendering. It's a low CCT lamp.

It could've been invented prior to the Edison lamp. It wasn't really an impossibility. It just so happened it wasn't.

But had it been the first invented, it likely would have had a big impact on the lighting field because it is very efficient and has a long life.

So however, I don't think anybody ever would have considered it as a standard for low CCT color rendering because the colors don't look right. And what I mean by that is this-- if you look at objects under a high pressure sodium lamp you can't determine what their color is under daylight from what you see. You just don't have good judgment of that.

Whereas with blackbody radiators, you do. It's easy to show that ordinary objects-- when you calculate their color under incandescent lamps, may differ a little bit from daylight, but in a way that people can understand and get used to and predict-- very importantly what's called metameric matching under daylight-- also predicts very nearly metameric matching under blackbody radiators or incandescant light.

So we don't know of a better source. And I'd just like to say though that there is an issue has been brought up in this regard, and that is the question of whether using the blackbody radiator as a source represents a constraint on chromaticity.

Is it necessary to have lamps that lie on the blackbody curve to get a high color rendering score if we're using the blackbody as the means of defining ideal color rendering? And the answer to that is no.

And actually later if there's time, I know Aurelien has some slides to illustrate this if we can get to that.

But I'll just say briefly because we have an excellent what's called chromatic adaptation calculation in CIECAM02 or CAMO2-UCS, it just isn't a constraint. So the fact that we are using blackbodies as the reference for color fidelity doesn't mean that to get a good score you have to lie on the blackbody curve. There's just tremendous freedom there.

So on that note, I will hand over to Aurelien. Oh! Pardon me. Sorry. The next slide's mine too.

There is one detail on the use of reference illuminants that we should mention. And that is that the transition from daylight to blackbody occurs with the current CRI at 5,000 K. That is above 5,000 K, we use daylight as the standard. Below 5,000 K, we use blackbody.

And that's fine, but it creates a little glitch which is illustrated in this chart that in a certain color space where we're showing how when you change from a 5,000 K daylight spectrum to a 5,000 K blackbody spectrum, there's a little change in color and actually a little change in the CRI scores that is kind of discontinuous at that point.

Nobody cared about it at all in the past because is never created a problem. But nowadays, it may be more important. And so the decision was made to eliminate that completely through a very simple procedure where the actual selected illuminant changes continuously from all daylight at 5,500 K to a 50/50 mix of 5,000 K daylight, 5,000 K blackbody at 5,000 K to all blackbody at 4,500.

And what that does if we look at the actual spectral distributions as shown here is it just causes a very slight gradual shifting that makes complete sense. It's very intuitive and appropriate, and it avoids the glitch.

Now, in terms of the changes that this has to the scores-- the actual fidelity scores that we will get-- they're insignificant. So really there's no reason to like this or not like this from that perspective.

However, it is important in terms of this transition. And as so many of you may know, a number of manufacturers are now or hope to bring out color tunable luminaries that could shift in CCT right through 5,000 very smoothly. And there's something terribly inelegant about being asked to make a sudden change-- right at 5,000, even if it's a small change.

And so this is an irritant that we have removed and we think is appropriate to do. And I think that concludes my portion of the discussion.

All right. So we'll take a few more questions now. I got some good ones coming in. So several of them were late to the color samples and the saturation levels. I see one here-- the 99 color sample swatches seem very pastel and not very saturated.

Another one-- sample set seems to exclude saturated colors. Is there a sample that is equivalent to R9? And how are saturated colors represented if we're only calculating with these other 99 samples?

Another question-- do we have any sense of how these standards work out with highly saturated colors? Can we rely on these metrics for art galleries for instance?

Aurelien, do you want to chime in on those?

Yeah. So I think the first thing I would say is if I disagree with some of the statements I just heard. The sample set includes some very saturated colors as well as some very unsaturated colors.

Just for those of you, for instance, who are familiar with the CQS color calculation method, which is part of the basis over which we built TM-30, the CQS was using saturated samples, and the most saturated samples of TM-30 are pretty much of equal saturation as those. So we are doing fairly high in saturation.

I think maybe the issue is just when it displays on a screen. It's not necessarily very convincing, but I think you would find that, in the real world, there are some saturated samples in here.

There was a specific question about R9. We have a backup slide about that.

There are different ways to evaluate red rendering in TM-30, and it so happens that there is one specific sample which has a very high correlation with R9 if you really want to keep track of that.

Did I address most of the questions, Mike? Or were there parts that I dropped?

I think that generally explains it. There's another related question here about showing the samples on the screen. I just want to point out that when we're showing those on a screen, it's really an approximate representation. It depends on your monitor. It depends on a lot of things.

We're not using that actual sample in any way. It's just a representation to help you out visually to think about the colors. We're only using the reflectance functions that are included.

A couple other questions about the samples. Are any of them the actual CRI samples? Aurelien do you want to answer that one too?

I haven't checked. I would say that's very unlikely. We had 100,000 samples to choose from. And I guess eight of those were in fact the CRI samples. I haven't checked if any of these made it, but I would think probably not.

One thing to point out though is that we've created these little cubic pixels in color space. So each of those CRI test samples was in one of those cubes. We've chosen as well a different sample-- could have been the CRI one-- from that same cube. You could find a set of the most similar eight color samples to CRI if you chose to.

Right. So it's correct that there are definitely samples inside our 99 which have a color very similar to the eight TCS.

Last question. We've got one more section to get through, but there's a few questions related to daylight. What exactly is it? Cloud cover? Is it constant? What type of daylight are you measuring? Lorne do you want to take that one?

Well, yeah. I'll say we're just using the exact same standard that was used in CRI, and I'm not an expert on that standard. But it's a blend of daylight measurements that have been made at various times and committees agreed were representative, and importantly, are representative in a defined, calculated way as a function of color temperature.

So we've heard no complaints with that system, and we're just adopting it directly.

OK. Let's go ahead and move on to the last section. I think, Aurelien, you kick that one off.

Yeah. Just have a couple comments and then I'll let you, Mike, tell most of the story.

So now we've discussed the color space, and we discussed the sample. So we have all the ingredients in hands to run a color rendering calculation, but we still need to run the calculation properly. And so this part is to tell you how we go from samples to scores.

And we follow kind of a hierarchy. So this slide describes that.

We start from a very high amount of data, which is the color shifts for the 99 samples of TM-30. From these, we can first compute a fidelity index, which is just the average color distortion for the 99 samples.

Or we can bin these 99 samples into different sectors, different bins of hue. And from that, we can generate various amounts of data. We can get the color vector graphic as well as a gamut index by averaging over everything.

So in the coming slide, we're going to show you how this is calculated. But I'd like to start with a quick refresher of what a color shift or a color distortion can mean.

So this is a sketch, which again, using the color space. You can think of it as CAMO2-UCS even though it's only a sketch. And let's assume I'm looking at a given object which has an orange tint in this color space.

So that object might be the food, an orange. And let's say that under sunlight it has a nice orange tint. Well, a given light source might distort the color of the orange to make it look more yellow, more like a lemon. This would be hue shift towards yellow.

Another source might make this orange look riper, a deeper orange. This is what we would call a saturating shift.

Yet another light source might make the orange look less saturated, less ripe, and we call this a desaturating shift.

So in general, for any given object, a light source might induce a color shift in any direction, which is going to be a combination of hue shift and saturating or desaturating shift. And this is the first thing we compute in TM-30.

So we take our 99 samples, and for each of them, we compute chromaticity under reference and chromaticity under test source. And we look at the shift between the two.

Now of course, this is just a sketch showing you a few samples, but we do this for the 99 samples that we use. And if you remember what Mike showed you at the beginning of the slide deck, this is quite similar to what is done in the CRI but in a different color space and with different samples.

Now, I will let Mike explain how we go from these color shifts to actual color rendition numbers.

OK. So you can see this slide now. We have a plot in A prime B prime space of each of the 99 color samples, and this is just one example of a test source and a reference condition.

So as Aurelien mentioned, we're calculating the chromaticity of each of those 99 color evaluation samples in CAMO2-UCS.

From there, we calculate the color difference using a basic Euclidean distance formula subtracting the coordinates in all three dimensions. So that's your delta e, jab-- jab's the color coordinate system, and i is the color sample 1 through 99.

So we can do that for all 99 color evaluation samples. This is just a graphical illustration of that. When we calculate color difference though, it's not a very useful number to us. So what we want to do then is scale it by the factor of 7.54 in this case. And that factor was derived a similar procedure that was used for CQS to give an approximately similar scale to what we were dealing with with CRI. So there's not some drastic change in the scale.

So we have the 7.54 scaling factor based on the scores of the CIE F1 to F12 illuminants, which gives us an approximate range similar to what we would see with CRI or CQS, but again, we don't have an exact translation from one to the other.

So we need to rethink about that scale a little bit as we discussed last week, and we're subtracting the numbers from 100.

So to get to our average value, Rf, that we explained a lot about last week-- we're simply taking the arithmetic mean of those 99 scores. And we discussed different averaging methods, but arithmetic was determined to be the most appropriate in this case. We're also applying a small transformation on the end. So there's actually a lower limit of 0.

It was a common misunderstanding with CRI that there was a limit of 0 when in fact you could have negative CRI scores. And just for the value of making this easier to interpret, we added that log transformation which really only applies to fidelity scores less than about 20 or 30. So nothing really practical for interior lighting.

Now, in addition to these 99 samples or the average value-- and again-- we talked a lot last week about the limitations of an average value. And you can see here that the average only tells us some representation. It doesn't tell us whether the samples are the reds that are having issues or the blues. Some reds can be good, but other reds might not be as good. So we can do other things beyond this average value.

Now, one thing we can look at-- and there was a question about this-- is skin tones. So if we look at sample 15 and sample 18, we essentially force those in the procedure to select color evaluation samples to these skin tones because we knew this was an important consideration for many specifiers.

So we can calculate the Rf skin by simply the arithmetic mean of those two samples, 15 and 18.

Another question that came up last week-- well, how do you pick two skin colors? And what are they?

Well, these were picked from a library of thousands of skin samples, and these two samples were ones that produced the highest correlation to if we had chosen all of them to calculate this Rf skin value.

All right. So now, Aurelien introduced the different branches here, and so we go to the 16 hue bins. So if we take these 99 samples, we can divide it into 16 bins. We number those consecutively going counterclockwise from the positive x-axis or the positive a prime-axis in the CAMO2-UCS.

So within each of those 16 bins, we can calculate the average chromaticity based on the samples that are in that bin under the referenced condition. So here now, we have 16 different sets of chromaticity coordinates-- don't necessarily correspond to any one of the samples but an average of all the samples.

We can in fact, then normalize the chromaticity coordinates for the reference condition to a circle. Then we can calculate the color difference between the reference and test condition for each of those 16 pairs and translate that vector onto the normalized circle.

If we can do that 16 times, we get this plot of vectors. We can connect those dots then to form the color vector graphic as we introduced last week.

So a couple more notes on the interpretation of that graphic. It shows hue shifts which are tangential to the reference circle. It shows decreased saturation arrows that are pointing into the circle, and it shows increased saturation with arrows that are pointing out from the circle.

That graphic really corresponds to these 16 hue bins, and we can calculate numerical indices for the bins as well. So there's a question that Aurelien sort of addressed earlier-- we could use, for example, the fidelity in hue bin one to let us know about the average representation of reds.

We could use hue bin eight to look at green and blues, for example. 14, more on the purple side of things.

We can look at just a fidelity value, which another question asks-- does this fidelity still penalize sources that are increasing saturation? And, yes.

So this is a true measure of fidelity, meaning any deviation, it's going to be penalized, but we've augmented that with additional information about saturation. So you can understand how exactly that deviation is occurring.

So we can see the plot below is the change in chroma in each of those bins. So if we're concerned what is exactly happening with those reds? So you saw in the previous example the reds were being desaturated-- here I can see, yes. My red fidelity is 49, and that's because I'm seeing about a 28% change in the chroma, a reduction in chroma, of those red samples.

So the final average metric is the average gamma value, and what we're doing with that is we're taking those 16 chromaticity coordinates. We're creating a polygon with both the test and reference conditions. We're calculating the area of those polygons, taking the ratio of that area and scaling it by 100 so that when we have a score greater than 100, we're indicating overall increase in saturation. And a score less than 100 is an overall decrease in saturation.

And again, that is on average. So all the limitations of average values apply here. But again, we back that information up with all this more detailed information in applications where that matters and for those who care to look for it.

So finally, the last technical slide. Really, all this combination of this core calculation engine and pairing these average values based on the same core calculation engine really leads to a cohesive two-axis system.

So we can see there's an obvious trade off between fidelity and gamut. Now, there's only one way to have perfect fidelity, and that is to exactly match the reference condition. Any time we're moving away from that condition, so we're decreasing fidelity, we can then be increasing saturation on average or decreasing saturation on average by moving below that 100 line.

So if we didn't, say, have a cohesive system, what might that look like? And so this is one example.

So if we pair the gamut area index with CIE Ra, CRI, you lead to this plot where the trade off between saturation and fidelity is much less apparent, and it becomes much more difficult to use and understand exactly what type of source you're going to get.

Because these two indices have different reference sources, we actually have multiple sources. There's multiple ways to have perfect fidelity, and so that inherent trade off between the two attributes of perception is lost.

So just to wrap up with some conclusions here, and then we're just going to have a couple minutes for questions-- TM-30's ready and available for use. You can get it from the IES web page. The Excel tool comes with it.

It offers substantial technical improvements between the color samples and updated color signs, each contributing to improve the accuracy and usefulness. It also expands the availability of information to counter the limitations of considering a fidelity metric alone.

And this single, cohesive method includes a variety of measures that really allows a hierarchy of information that's most suitable depending on what you're using it for.

We can use those measures together as a whole to determine the most suitable source for a given application or user group because, at least in my opinion, there's no universal preference, preferred source, for all applications of light sources.

So with that, here's a slide that just provides some additional resources, and we'll open it up to a couple more questions. And I hope Lorne and Aurelien have been looking at the questions because I'm just getting to them now.

Yes. I have been, and I have one question that I think sounds very interesting and would be worth commenting on by one of us. Actually they're two questions that go together. One is-- in the version of the Excel spreadsheet available from the IES, is it possible to see the macros that are in part of the calculation? And another sort of related question is-- will there be a Matlab version available at some point?

Sure so IES has requested that the macros are all locked. And that's simply because if people start manipulating the spreadsheet and then you could use it to produce results and it would look like it was coming from an official version of the spreadsheet but it wasn't, that's a bit problematic for IES.

So these worksheets are intended to serve basically as a reference standard that everyone can go back to, and this is the official calculation of what you should be able to calculate in anyone else's software. And we expect that other people will be developing software as well that will probably be more user friendly than the tools we developed.

I think they're great tools, but we're not computer programmers. So I'm sure others can do much better.

What was the other question? The one about the tools.

Is there any plan for a Matlab version to be available?

So, no. The IES probably won't do any additional development on tools. I know already though that several companies that specifically sell essentially color calculation software, or manufacturers have implemented this into their own color calculation software.

So the TM lays out all the steps necessary to do that. You can look at the basic calculator and see all the equations and how they were programmed there. And hopefully that's helped you with what you need.

There was one other key question I think I'd bring up unless, Aurelien, you have a favorite that you were hoping to bring up.

The question is-- which reference samples do you prefer for LED fixtures?

And maybe I'll answer that one if you like, Michael. These reference samples are all used for all sources.

There isn't anything special about LED lamps. They do enable sharper spectral features to exist, but light is light. And the intent is that all 99 samples are used for all calculations of Ra and Rg-- Rf and Rg.

All right. I have one other question, and we might have time for just a couple more. We're hitting about our time limit. It says, will you talk about the whitebody curve

So this whitebody idea has been something that's coming up recently that the perceived color of neutral white, or the preferred color of neutral white, is not necessarily on the blackbody.

Now I'd like to point out that chromaticity is not something that's considered in color rendering or in TM-30 specifically, but we can consider chromaticity along with color rendering and pair them together to choose an appropriate colored source for an application.

There was some talk and discussion as TM-30 was being developed about, could we have the reference source actually be on the whitebody curve?

And that's a bit of a tricky question, and one of the issues we've stuck with what we've stuck with is the CIE defined sources is that there is a numerical definition of them. To create a reference source on the whitebody curve, we would essentially have to make up those sources on our own, which is probably a task in and of itself.

Now, someday down the road if that task is completed, it would be perfectly reasonable to substitute those reference sources and revise TM-30. TM-30's not a fixed document. It's not set in stone. And just like CRI was revised over the years, I imagine TM-30 could be revised in the same way.

So here is a couple extra slides we had put together. One was about the correlation for R9.

So if you look at CES sample seven, you can see a very strong correlation in the scores for that with R9. So if you're particularly interested in that sample, you can use that. Or if you're interested in reds in general, I would suggest using the average from hue bin one.

There was nothing particularly special about R9 other than it was the only red sample available for any of these evaluations. So limiting your characterization of red to one type of red might not be very good because you're using a very limited set of information to draw inference about a broader set of red color samples.

But more directly applicable to what I was saying, can TM-30 be used to evaluate off-Planckian sources? Or what are the limits?

So if we move away from the reference condition, there is a slight drop in the maximum theoretical Rf of any of those sources. But when you get pretty far away, it's still a pretty insignificant drop. You can still get a really high Rf. I don't think anyone is concerned about a difference of 97 and 96 in terms of Rf. Those would be considered very good color fidelity scores.

And we can look and we can do analysis too that this is common to all color rendering sources that are based on a reference calculation, which is the principal method that has been used for all of the recent proposals. So CRI, CQS, Rf all have this feature where if you move very far off the blackbody, it's harder to achieve very high scores.

Now that said, one last bit of information from me-- I'll let someone else talk-- is that as you're moving off the blackbody, yes, you might not be able to achieve the highest fidelity score, but often you can increase the gamut index. So there are trade offs to be had there both with color rendering, with color chromaticity, and white perception preference and gamut.

So any closing comments from you Aurelien?

Oh I think we've lost Aurelien.

Any closing comments, Lorne. No. Thanks very much.

All right. Thank you all for attending. Just a reminder, we'll be posting a video of this presentation with a few of our little gaffs cut out-- sorry about the technical difficulties there with the computer-- and a PDF version of these slides.

You can apply for your CEUs with the IES, and thank you for listening to this webinar sponsored by the US Department of Energy and the Illuminating Engineering Society.