RAMESH RASKAR: All right. So let me switch over to this topic. And let's see some cool demos. So this particular project that Kimo Johnson and [INAUDIBLE] Adelson built, called retrographic sensor, also won the best demo award at CVPR. So we saw this chart last time. They're already selling 2.5 billion sensors in the next year or two per year. And this is the forecast made in 2006, 2007. So it might have changed.

And if you see the integration of cameras in mobile phones, a natural question is, will we have-- will we even think about our digital still camera as a standalone entity in coming years? And if you think about the wristwatch, I think most of us don't wear wristwatches anymore. Knowing what time it is is not a difficult problem anymore.

I don't need to spend a lot of money. Or I don't have to tether myself to an additional device to know what time it is. And will we be in a similar situation about image? Will we even have a standalone camera for any purpose? So I just want to take a couple of minutes to see what opinions you have.

According to Nokia, more than 50% of the people who bought N95 got rid of their point-and-shoot camera And Nokia sells about a million phones every day. They sell 400 million phones a year. So they sell more than a million phones every day. So these are staggering numbers. Which is the largest camera company in the world?

AUDIENCE: Nokia?

RAMESH RASKAR: Sorry?

AUDIENCE: Nokia [INAUDIBLE].

RAMESH RASKAR: Nokia, right. It's not a traditional camera company. And the same answer for, which is the largest computer company in the world?

AUDIENCE: Flextronics.

RAMESH RASKAR: Oh, yeah, Nokia doesn't build anything of their own, of course. They owe EM everything. But still, they're the largest camera and computer company in the world as well. So all right. When do you think of camera as a standalone device will completely disappear?

AUDIENCE: It'll never completely disappear.

RAMESH RASKAR: And by completely, I mean less than 0.1% of the population carries it, basically. Something that's-- it's like saying whether the film camera will disappear. And I believe it's gone.

AUDIENCE: Oh, but they're going to be gone in different ways. So camera and digital cameras are going to be gone. And then, they're going to be everywhere. And film cameras are gone in that nobody uses them.

AUDIENCE: What?

RAMESH RASKAR: I'm sorry

[INTERPOSING VOICES]

[LAUGHTER]

RAMESH RASKAR: I'll give you an invented thing. You don't want to answer the film camera question. You'll love it. But when will the digital camera disappear altogether? You don't have anything against digital cameras, though, do you?

AUDIENCE: Well, no, I don't have anything against digital cameras. But it depends on your definition of a digital camera. If you're just talking about point-and-shoot cameras--

RAMESH RASKAR: A standalone-- a camera-- a device that's built specifically for the purpose of taking photos.

AUDIENCE: So if you're not going to be a professional photographer, then the average consumer, it's probably just going to disappear maybe in 10 years?

RAMESH RASKAR: 10 years.

AUDIENCE: Five years?

RAMESH RASKAR: All right. And either-- anybody thinks it'll happen in less than 10 years? Let's take someone over there.

AUDIENCE: Yeah, I think around five [INAUDIBLE].

RAMESH RASKAR: In five years? There'll be no standalone consumer digital cameras.

AUDIENCE: Yeah, I think in just a couple of years because if you think about it--

RAMESH RASKAR: In two years?

AUDIENCE: Yeah.

RAMESH RASKAR: Wow.

[LAUGHTER]

Let's call all the camera companies.

[LAUGHTER]

[INTERPOSING VOICES]

AUDIENCE: --she's already switching over to emphasizing video. And then also, SLRs are starting to be video also because they're not just normal cameras anymore.

RAMESH RASKAR: Right. But I meant, video cameras are still cameras, the same thing. I'm just saying, will we have standalone devices that only goes to--

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: Yes?

AUDIENCE: There are cameras that allow you to upload your [INAUDIBLE].

RAMESH RASKAR: Right.

AUDIENCE: And there's no reason why it just wouldn't be on a computer, the actual [INAUDIBLE] device [INAUDIBLE].

RAMESH RASKAR: Exactly.

AUDIENCE: So basically, it's converting both the cameras [INAUDIBLE], not just the acquisition.

RAMESH RASKAR: Right.

AUDIENCE: And the other [INAUDIBLE].

RAMESH RASKAR: Right. You're right. It's going to be some, kind of, fusion. But is the camera going to become a phone? Or the phone is going to become a camera?

AUDIENCE: [INAUDIBLE]

[LAUGHTER]

RAMESH RASKAR: I think in the back.

AUDIENCE: I would say a century.

RAMESH RASKAR: A century. Wow.

AUDIENCE: Yeah, the same way that computers brought us the paperless office and the end of books. And we no longer have a stage, theater, or cinema. We've been predicting that for a long time [INAUDIBLE].

RAMESH RASKAR: So that's a very interesting comment. What's unique about paper or watching movies that may or may not apply to a device?

AUDIENCE: But in response to what you said, the need to capture images won't disappear. But the fact that there is going to be one device that its sole purpose is to capture images will disappear. And it will be a device that it's either a phone, and capture this, and [INAUDIBLE], and [INAUDIBLE].

AUDIENCE: Yeah, the way we print things has changed. But we still have [INAUDIBLE].

[INTERPOSING VOICES]

AUDIENCE: That's why you're doing the image, though, because you're shooting stuff on a screen because you want the image quality. So maybe you [INAUDIBLE] enough or simulate it that [INAUDIBLE].

RAMESH RASKAR: Yeah, but it is a hypothetical scenario. If I can buy a phone whose image quality is sufficiently good compared to a standalone still camera, that's the question. Yeah, assuming that the image quality is going to be good enough. Let's ask somebody down here.

AUDIENCE: Sorry, go.

RAMESH RASKAR: Yeah.

AUDIENCE: Yeah, I actually really agree with what he said. I actually think it'll never really disappear for a couple of reasons. I think--

RAMESH RASKAR: 0.1% of the population.

AUDIENCE: All right. So I actually will be curious today how many people carry phone cameras. I'm curious.

RAMESH RASKAR: One billion people carry a camera in the pocket.

AUDIENCE: But so one reason I think is that there's not only image quality. But there's the ergonomic interaction.

AUDIENCE: Yes.

AUDIENCE: And I think the reason why a lot of people carry DSLR is not just for the image quality, but for having things available, and buttons, and having human hands that are certain sizes, and people

[INTERPOSING VOICES]

RAMESH RASKAR: Sometimes, that's heavy enough and something to look cool with and so on.

[INTERPOSING VOICES]

[LAUGHTER]

AUDIENCE: So--

RAMESH RASKAR: Is it for function or just for

[INTERPOSING VOICES]

AUDIENCE: No, the heaviness does add a function because it stabilizes the image a little bit.

AUDIENCE: Yeah, but I also think that there's something else too. I'm actually unconvinced in general that devices converging is necessarily good. Friends of mine that I tell this to say that I'm an exception because I carry two cell phones. And I think I'm carrying three cameras right now.

RAMESH RASKAR: Yeah, two cell phones will never converge.

[LAUGHTER]

AUDIENCE: Well, the amount of phones that have two Sim cards

[INTERPOSING VOICES]

[LAUGHTER]

RAMESH RASKAR: [INAUDIBLE]

AUDIENCE: No, I think there are certain advantages to having, actually, redundancy in devices and things. So I definitely agree that digital cameras might have WiFi connectivity or other things. But I suspect that a lot of people will carry separate things that are their primary purpose as imaging and a separate thing itself.

RAMESH RASKAR: Right.

AUDIENCE: And then, they also have a camera in it.

RAMESH RASKAR: Well, there will always be a film camera in [INAUDIBLE] house.

[LAUGHTER]

Even 20 years from now. But we're talking about 0.1%. So let's take a quick vote and move on. So how many people think it's-- let's do the reverse. So we'll say, two years from now, how many of you think will a standalone imaging device will disappear? Kevin? No? All right. We have one.

AUDIENCE: No.

RAMESH RASKAR: Do you want to say very quickly why? Because you--

[LAUGHTER]

AUDIENCE: It would be-- so far, the image quality has been the problem.

RAMESH RASKAR: Right.

AUDIENCE: There's just not quite enough reliance on the sensors that you can fit into a phone. But I think people are finding ways to get around that with software and with optics.

RAMESH RASKAR: Right. Oh, by the way, this--

AUDIENCE: And with the sensor, actually. There's a whole new generation of sensors coming out that allows you to [INAUDIBLE].

RAMESH RASKAR: Remember, right now, the total standalone devices for imaging is 10% already. This is optical mouse, which is not really a camera. We can ignore that. But mobile phone camera, [INAUDIBLE] cameras, gaming and so on. So it's already 10%. And we're talking about 0.1%. So let's move on. And just, let's take a quick poll. So two years, we have only [INAUDIBLE].

AUDIENCE: Quick question, I guess. Is that even a decent metric? Would it be better to say, how many photos are taken? Because a lot of people carry cell phone cameras, but are using the [INAUDIBLE]. My mom doesn't use her cell phone.

RAMESH RASKAR: Right.

AUDIENCE: But she has one.

AUDIENCE: Yeah.

RAMESH RASKAR: The next class, we'll talk about, how long will it take before photos disappear? But--

[LAUGHTER]

--that's the next conversation.

[LAUGHTER]

So it's like saying, how many people write with their own handwriting? It's the same situation we want to see very soon. But that's for the next class. So two years, we have only one. Five years? Three or four. 10 years? 15 years? So I guess almost everybody because-- and never? Wow. Wow. All the power to you.

AUDIENCE: I say one additional comment. We're thinking about this population. But here, in most of the world, people cannot go and afford this separate camera. They're going to buy a phone.

RAMESH RASKAR: A similar point. An excellent point.

AUDIENCE: [INAUDIBLE] 1%.

RAMESH RASKAR: Yeah.

AUDIENCE: It doesn't change that much.

RAMESH RASKAR: When the remaining five billion come on board.

AUDIENCE: Right.

RAMESH RASKAR: Yeah, that's a good point, actually.

AUDIENCE: So in camera phones.

RAMESH RASKAR: Right. Yes, Jeremy?

AUDIENCE: Yeah, I have a prediction. I think that people will still have many devices, like an Apple device. And if you look at Steve Jobs, you have the iPhone with camera and the iPod Touch with camera.

RAMESH RASKAR: Right.

AUDIENCE: Now they are an iPhone without [INAUDIBLE].

RAMESH RASKAR: Right.

AUDIENCE: So it's interesting.

RAMESH RASKAR: That's just a marketing gimmick. But--

AUDIENCE: Yeah, but it's interesting to think of marketing in this respect. And I think the point is they [INAUDIBLE].

RAMESH RASKAR: Right.

AUDIENCE: Some people can [INAUDIBLE] device.

RAMESH RASKAR: Right.

AUDIENCE: And the mobile phone makes sense because communication is really [INAUDIBLE].

RAMESH RASKAR: Yeah, very soon, you'll be able to buy a burger with a camera in it.

[LAUGHTER]

That's your--

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: What's the toy called for chicken? The happy toy.

AUDIENCE: The Happy Meal.

RAMESH RASKAR: The Happy Meal.

[LAUGHTER]

And you'll know what you ate and how many calories

[INTERPOSING VOICES]

[LAUGHTER]

RAMESH RASKAR: It's a lot. But--

[INTERPOSING VOICES]

AUDIENCE: It will trace the burger through your digestive system?

RAMESH RASKAR: Yeah, it will show you how happy you were and--

AUDIENCE: And then, when you get it out, it's [INAUDIBLE].

AUDIENCE: Great.

RAMESH RASKAR: Right.

[LAUGHTER]

AUDIENCE: Yeah, in this graph, the number [INAUDIBLE] has also increased followed by the same proportion as the number of mobile phones.

RAMESH RASKAR: Exactly. It's mostly mobile right now.

AUDIENCE: Yeah, but see, the network of digital cameras is really part of the

[INTERPOSING VOICES]

RAMESH RASKAR: It's not growing at the same rate, unfortunately. So--

AUDIENCE: [INAUDIBLE] you can't buy a phone without it. It's hard to find a home without a camera. So it is unfair to look at that.

RAMESH RASKAR: But that's the whole point of this class. I think we are at a stage where people are saying, oh, cameras are cheap enough. By the way, do you have an idea of how cheap a camera is today?

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: For a device maker, how much does it cost them to pay for a camera? If they would attach a camera, how much does it cost?

AUDIENCE: $1 [INAUDIBLE].

RAMESH RASKAR: $1. Anybody else?

AUDIENCE: [INAUDIBLE] $5.

RAMESH RASKAR: It's $0.20.

AUDIENCE: What?

[CHATTER]

RAMESH RASKAR: So when I said it will come with your burger, I'm not joking. All right? Yeah, of course, it doesn't have power. It has electronics. It has objects. It has sensors. And it has a compression engine. All right? It's $0.20. So things are changing rapidly. And to answer your question on, OK, you cannot buy a device without a camera in it anymore, the problem is, right now, we don't have enough services that go on top of those cameras.

But imagine if people in this room say, wow, a billion people have a camera. Let me try to see if I can build something that really exploits that. Or let me see if I can change the game a little bit, add a little bit extra features, maybe add a thermal sensor to it, maybe add UV light to it, whatever it is.

Maybe I'll make it into a camera so that instead of $0.20, now it costs me $0.23. It'll completely change the game. And the same way we get addicted to our devices and we just can't live without them anymore. Hopefully, cameras will play a similar role, that you will be forced to use the camera and it won't be just an additional feature that never gets used. So--

AUDIENCE: Did you hope this or [INAUDIBLE]?

RAMESH RASKAR: About what?

AUDIENCE: That you'll be forced to use a camera?

RAMESH RASKAR: Not forced, but you'll be encouraged. How about that?

[LAUGHTER]

It's like saying, are you being forced to use a credit card?

AUDIENCE: Yeah, that's what I actually felt like [INAUDIBLE].

RAMESH RASKAR: Yeah.

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: That's another discussion I'm going to have [INAUDIBLE].

[LAUGHTER]

All right. So taking notes. As you can see, a lot of our discussion will be not on the slides. So Sam's taking the notes today. And what you need to do is the slides will be online. So you don't need to capture what's on the slides. And you don't need to capture all the information that's coming up. For example, JB had a comment on a new camera or the other comments in the back. So you want to capture that in the slides or anything I mentioned.

And also, summarize some of the question and answer sessions. And we'll draw some-- we'll have some demos, [INAUDIBLE] pictures. And I'll do some doodles on the board, and take a photo, and so on. And we'll have one student assigned for each class if you're taking for credit. And I encourage you to just use a laptop because you can, one, take notes faster. And you can also look up some information very quickly.

And then, you can work with me over the weekend. And on one day, we'll post it on Stellar. Is everybody familiar with Stellar website for MIT? How many of you know about the Stellar webpage? Everybody is familiar? And if you don't have access, if you're not taking the class for credit, then you may not-- I think you should be able to access. It's open to anybody in the world. So you can even send it to your friends. And they can look at just the slides. They won't get a lot of the other information, of course.

But if you cannot access it, just send me an email. And I can explicitly add you as a guest on the Stellar website. The one benefit of adding explicitly is that, sometimes, the announcements go only to the people who are taking the class for credit. It could be about exams or other things. And if you want to be part-- if you want to participate in that, then you'll get those emails as well.

So assignment one was about lighting. And that's what we'll be talking about today, very different ways of capturing light. Does anybody have questions? Because there's have a few things you had to do. You had to have a committed source code. Or if you used a GUI-based approach, Photoshop or something, then you need to show me a lot of intermediate results, input and output images. The images should be captured by yourself with your own camera.

If you don't have-- for the first assignment, maybe you can use a cell phone camera. But see if you can buy a cheap camera that has a manual mode. You can buy a pretty good camera for less than $150. I recommend the Canon A series. It usually has a manual mode. And another benefit of the Canon series is that we have very good SDK. So you can control the camera from your laptop or from your PC. So I recommend the Canon A series to buy.

And then, you must create a webpage where you will host your solutions for your assignments. And then, you should send me a link. And what you update on the Stellar is just a link. You're not going to upload all the images and so on. And then, it's perfectly fine to use software you find online. It's perfectly fine. Don't use your colleague's software in this class or software people wrote in this class last year. But you can go online. Go to MATLAB repository. And if they have a function for doing x, y, z, it's perfectly fine to use it.

And then, we have a Flickr group page. I believe you got an email from me about the Flickr group page. And all your final results, sorry, input and final results will be on the Flickr page so everybody can see it. And we can write comments about each other's work. And this will be a good trial run towards our final project, where we will be doing a lot of commenting on each other's work, giving a lot of feedback, and critiques, and so on. So three things, Stellar, your own webpage, and the Flickr page. Any questions?

All right. So this was simple. And if you have more time, you probably want to do in your assignment something that looks like this, where you can do some beautiful light. All right. So some of the assignments, I think we already discussed it, will look like this. And let's start with some interesting ways you can think about illumination.

So here's a photo from One Kendall Square. This is [INAUDIBLE] here and so on. And even if you have been to Kendall Square, this photo, it's somewhat difficult to understand what's going on. You don't even know how many stories this, I guess it's the [? Treper Labs ?] building, has, for example, from this photo and so on. So imagine if, magically, you can convert this photo into this photo from here to here? What are some tricks you can use to do that?

AUDIENCE: Wait 12 hours?

[LAUGHTER]

RAMESH RASKAR: [INAUDIBLE]

AUDIENCE: [INAUDIBLE]. They have Photoshop's Shadow Highlights feature.

RAMESH RASKAR: Yeah, you can try to stretch the [INAUDIBLE]. Or you can try to take a really long exposure photo. But yeah, this is really, really dark. There's almost nothing there.

AUDIENCE: [INAUDIBLE] another photo, you can [INAUDIBLE].

RAMESH RASKAR: Exactly. Who's saying that?

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: All right. Good. So you just cheat. This was actually taken when I was working at MERL. And this will be from my office, actually. It's a much nicer building than the office I have right now.

[LAUGHTER]

AUDIENCE: This campus is nice.

RAMESH RASKAR: Sorry?

AUDIENCE: This campus is nice.

RAMESH RASKAR: Yeah, I like the brick texture. It's beautiful.

[LAUGHTER]

And just take the photo after 12 hours, in the morning. Actually, I took a photo at 6:00 AM when there were very few cars on the street. And somehow, you want to fuse these two photos into a photo that looks like that. So the static parts are captured from daytime. And all the dynamic parts with the cars, and the Christmas lights, and so on are captured from the nighttime. So you want to make some intelligent decision, which when-- which pixel comes from where?

AUDIENCE: The color temperature is off.

RAMESH RASKAR: And the color temperature is off. And you ought to make some artistic decisions about that. And you'll always have some issues, like this one. I think this guy, I waited all night long. But he was part of my class. He just didn't move. So you can see that.

[LAUGHTER]

You can see that. So it's a context-enhanced image. And we're really exploiting natural illumination to capture a new photo. Yeah?

AUDIENCE: So how was this [INAUDIBLE] to you what [INAUDIBLE] algorithm or--

RAMESH RASKAR: Yeah, it has to be an algorithm. So this is what you can do, just one approach. But maybe in your assignments, you'll come up with another approach. In this case, you can just take-- just compute the scene contrast. You can just take a five-by-five window and find pixels that have very high-variance. And you can create a stencil like this that says, oh, all these pixels look interesting.

And this part here, clearly, there's nothing. So I should not take that from the nighttime image. And then, I can create-- I can use the stencil. The black pixels will come from daytime. And the white pixels will come from nighttime. And if you just combine that, combine those two using that stencil, you get a reasonable image already. But it will look extremely ugly because the transition from here to here, from nighttime to the daytime, will not look very natural. So what can you do? Any solutions?

AUDIENCE: Blur the mask [INAUDIBLE].

RAMESH RASKAR: Blur the mask. You can do that. But then, the edges of the building will get very fuzzy because it looks like part of the building was in the daytime and part of the building was in the nighttime.

AUDIENCE: Could you just start-- could you just say how you made the mask again? I--

RAMESH RASKAR: This mask?

AUDIENCE: Yeah.

RAMESH RASKAR: So in the simplest case, you can just say, given the pixels aren't bright enough. That is, imagine zero to 255. Anything over 150, mark it as [INAUDIBLE]. That's the simplest thing. But it's not so good. A slightly better way of doing that is you go in a window of, say, five-by-five pixels. And if all the 25 pixels are the same, then maybe it's not very interesting. Here, all 25 pixels are the same. Or in this region, all 25 pixels are the same.

But if there's enough variation between them, if I just take the variance or the standard deviation of those 25 pixels and it's high enough, that looks like there's some information in those 25 pixels in a five-by-five window. And you'll have that center of that five-by-five window as something that's interesting. Yep?

AUDIENCE: One thing you could do for [INAUDIBLE] the buildings is that you would shrink the components that are not [INAUDIBLE].

RAMESH RASKAR: So you can use some a graph card approach and find some connected components and so on, like that?

AUDIENCE: [INAUDIBLE] a little bit, you could have taken any immersive photos and just, between them, defined motion or [INAUDIBLE].

RAMESH RASKAR: Great idea. Great idea, especially for something that's moving to find that.

[INTERPOSING VOICES]

RAMESH RASKAR: But you still have to take some data images to fill in the static parts that are dark.

AUDIENCE: Yeah.

RAMESH RASKAR: But that's right. In fact, that you have to do that for cars because some cars, the center of this car is too dark. But it's still important to us. So this is what simple processing would do. But maybe you want to do something smart. So this is just a zoomed in version of that. It's trying to capture-- all these windows did not have lights on, you see here.

But there's one window with a light on. I think this is the scaled up after biogen building, Amgen building. And it captures that. But then, it creates this ugly artifact around that. So you want a very nice transition between the two. So the solution for that is actually called a gradient dom infusion. And that's just a fancy way of saying that instead of worrying about absolute intensities, I'm going to worry about differences between every pixel.

So I'm going to take a pixel x plus one and pixel x and find the difference between them. And I'm going to blend those ones. So this is what would happen if you just blend the intensities. And this is what would happen if you blend the differences. Now if you blend the differences, which is just the forward difference, then the image that you will get will be also made up of forward differences.

So to go from a forward difference back to the signal, we must do integration. And in 1D, it's very easy. And we'll study that later. But in 2D, it's quite challenging. So it's basically doing a 2D integration from all the forward differences and putting the two together. Again, I'm not going through the details. We'll study this more. It turns out you can create various very aesthetically pleasing fusions or blending between different parts. Yeah?

AUDIENCE: What if-- this is just an example of a night and day. And what if you multiply the images and then normalize them?

RAMESH RASKAR: You could try different things.

AUDIENCE: Because the dark parts would come through. And the light parts from the day would also come through. And they might actually merge a little bit [INAUDIBLE].

RAMESH RASKAR: Right. So, Nina, these are some of the things-- it could work in one scenario, but not the other. You're right. And this is exactly what I want you to do in the assignment. The assignment gives you a very simple and very easy problem. But instead of taking pictures under two different flash table lab conditions, you could take a picture under two time instances, one in the daytime, one in the nighttime, or under two different polarizations or anything, and then fuse them.

Instead of fusing color channels, you can fuse intensity channels. Or you can fuse the forward difference channels and so on. One great software, it's on the website, I would like you to use for testing is called HDR Shop. And it's available for free. It's from a group at USC led by Paul Debevec.

And I highly recommend that because it certainly isn't Photoshop. If you use HDR Shop, again, even if you're doing MATLAB assignments, you can download HDR Shop. And it allows you to do some [INAUDIBLE]. You can sample images [INAUDIBLE]. You can subtract images. You can do forward differences. You can do volume densities and all those things. So it's a really good software for doing arithmetic on images.

And the other [INAUDIBLE] is done in floating point. It's not trapped [INAUDIBLE]. So let's say you want to multiply two images. And the intensities are at 200 and 200. It's 40,000 [INAUDIBLE]. And Photoshop only supports floating point numbers. But HDR Shop will support that. [INAUDIBLE].

So even before, sometimes, you're writing a MATLAB program, you can very quickly do some visual inspection on this and [INAUDIBLE]. Another thing a lot of people forget about when you're doing assignments or projects that involve images is don't work on the whole image. Work on a very tiny part of the image. Just take a 100 pixel by 100 pixel crop, largest size, but just a crop.

So you have some two megapixel images. Don't try to run your core on a two-megapixel image. It might take forever. Just take a very tiny part from a very interesting part. [INAUDIBLE] run all your code on that. And when you feel that all your procedures are working [INAUDIBLE], then you can go back to maybe some larger [? optical ?] image.

So when I was working on this portrait, actually, I was very inspired by this surrealism, AR surrealism, where René Magritte and all that came up with *Empire of the Lights.* I'm sure a lot of you have seen this painting, where he created this very stark, disconcerting positioning. You have bright daylight here. But the bottom part of the image is a nighttime scene. And he played with a lot of this juxtaposing of disconcerting elements.

And the question is, can photography create something that is surrrealistic, not always photorealistic, but surrrealistic? And when we come to a discussion about, will photos survive in the future, this is exactly the question that painters ask themselves when cameras are measured. There was a lot of interest in creating photorealistic paintings.

And when camera came around, they all scratched their heads and said, wow, we need to move on and do something else. We cannot create photorealistic paintings anymore. And then, we had pointillism and surrealism. And now, it's just abstract. We don't even care about representing geometry, and reflectance, and so on.

And the question is, should cameras worry about capturing intensity, and shapes, and geometry? When I check on Flickr, there are hundreds of images of buildings like this. What's so great about taking yet another photo of yet another building? What I want to create is images that are somehow more expressive and more real. So that's another debate, whether photos [INAUDIBLE].

I personally, by the way, have completely given up on camera. I don't-- I barely take photos when I travel and so on. It's just one of those things. I'm well beyond the stage of taking photos. And I rarely get impressed with beautiful photos. But these look nice. But I never get impressed with that. And hopefully, the remaining six billion people will also start challenging the notion of camera as a device that captures photorealism. People will challenge that notion just like the painters did during the Renaissance and [INAUDIBLE]. So any thoughts, [INAUDIBLE]?

AUDIENCE: Huh?

RAMESH RASKAR: Any thoughts?

[INTERPOSING VOICES]

AUDIENCE: There-- you've never seen a photo done by a photographer, let's say, Richard Avedon or Ansel Adams that you really liked, that

[INTERPOSING VOICES]

RAMESH RASKAR: It's beautiful. But I'm not impressed.

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: Can you say it louder? She said, what about Ansel Adams and so on? Yeah, back then--

[INTERPOSING VOICES]

RAMESH RASKAR: --when they did it, it was impressive. But now, if somebody shows me something as good as Ansel Adams, it's great. But it's not interesting.

AUDIENCE: Well, you should look at some of Richard Avedon's more recent works. He does some pretty creative things. There's one, he use a skeleton in some of his photos. And it's very serious.

RAMESH RASKAR: Yeah, so the content sometimes is impressive.

AUDIENCE: Right, yeah.

RAMESH RASKAR: But the art of photography. Comment back there? Somebody had a comment back there? All right.

AUDIENCE: I had one [INAUDIBLE]. I'm not sure you can separate both the technique from the content. So this is really discretion. But I think they can come together in creating and influencing each other's thoughts.

RAMESH RASKAR: You definitely need better and better tools and technologies to be able to create something that's really expressive, really, really beautiful and creative. But there was a time when photographers could impress us based on their techniques.

The guy with the biggest camera was called a professional photographer, not the guy with the best eye and somebody who has the patience, and aesthetics, and all of those things. And hopefully, now we have separated the two. Just because the guy has the best gear doesn't mean he's a great photographer anymore. And that's what I mean by-- yes?

AUDIENCE: [? Great book ?] on that topic as well, going back to old master techniques. It's called *Secret Knowledge* by David Hockney. I don't know if everybody else has read that [INAUDIBLE] all the different

[INTERPOSING VOICES]

RAMESH RASKAR: Can you just repeat? Is David Hockney--

AUDIENCE: David Hockney. It's called *Secret Knowledge.* And it's going through all-- he worked backwards based on weird artifacts and their paintings to figure out how they would make weird optical devices that could create the original artwork. And that goes back to the same concept of technique, and artists, and where those two

[INTERPOSING VOICES]

AUDIENCE: So there were from Ricoh?

RAMESH RASKAR: What's that?

AUDIENCE: From Ricoh?

RAMESH RASKAR: What do you mean? What?

AUDIENCE: The company Ricoh, he's from that.

RAMESH RASKAR: What? David Hockney.

AUDIENCE: The painter.

RAMESH RASKAR: Yeah.

AUDIENCE: He's a famous painter.

RAMESH RASKAR: Oh, sorry. Who's the guy from Rico who did all the same analysis? But this is the one where they looked at--

AUDIENCE: It's an interesting read if anybody's interested on the history of how these optical techniques played into the role of artists [INAUDIBLE]. It's controversial

[INTERPOSING VOICES]

RAMESH RASKAR: Yes, exactly. I think we're talking about the same thing. It's very controversial. And he claims that the painters knew about perspective and so on even before the Renaissance and so on.

AUDIENCE: Yeah, there's a lot of interesting backwards scientific discoveries that he did based off your artifacts in perspective.

AUDIENCE: Yeah, I think it's David Stork.

RAMESH RASKAR: David Stork

[INTERPOSING VOICES]

AUDIENCE: --Ricoh.

RAMESH RASKAR: Exactly.

AUDIENCE: Yeah.

RAMESH RASKAR: Is that the same thing we're talking about?

AUDIENCE: Different but maybe related?

AUDIENCE: I think they do similar things. David Stork writes about optical projections for planes. And so it's probably similar.

RAMESH RASKAR: So David Stork and David Hockney. All right. My laptop is recording again. That's fine. So yeah, so I think that's a great challenge we have about how-- the same way a camera put photorealistic paintings. They made them boring and basically put that breed of painters out of business.

What will be the next imaging paradigm that we'll put to this camera that would make these cameras boring, obsolete, and out of business? Because there's only so far you can go with a device that records light and tries to be realistic with a good signal-to-noise ratio converting photons into electrons. That's not what humans do. We don't see with our eyes at all. We just record with our eyes. And we see with our brain.

And right now, there is very little suppression in our imaging devices about sensing and seeing. But the whole concept behind computational photography is that these two processes are completely separate. They can be decoupled. You can sense in some crazy way with some crazy mechanism and then use a lot of computation to create images or create visual experiences that are very different.

And if you look at-- Dan in my group and others have put up together this really beautiful digital totem in our area. And it's constantly streaming the most interesting images on Flickr. And you stand in front of that, you will realize that if anybody is saying that the goal of a camera is to mimic a human eye, and that's what makes it a good camera, that notion will be challenged, because most of those photos which are tagged interesting by thousands of people on Flickr are actually the photos you don't see with your eyes.

It has some really crazy focus. It has very different color response curves. It has very different zoom and so on. It's basically things-- people think it's interesting when it's not what you see with your own naked eye. And that's what the goal-- if you take the concept for-- right now, people are trying to use cameras that are built to mimic the human eye and pushing them to create things that don't mimic the human eye.

If you take that further, why not start building imaging platforms that have nothing to do with capturing a 2D perspective photo? And that's what we'll see real soon. So I'm looking towards an imaging platform that can just create abstract visual art. I don't know what that will be. But go ahead.

AUDIENCE: I guess this is more of a question or a topic for your discussion. But what do you imagine the-- what is the fundamental photography or class of images that makes it lasting as opposed to the art tied to technology, which is batty. In the past year or so, [INAUDIBLE] photography. And they

[INTERPOSING VOICES]

[LAUGHTER]

RAMESH RASKAR: Right.

AUDIENCE: So it's entering the life of kitsch.

RAMESH RASKAR: Right.

AUDIENCE: Or even in HDR, you see a lot of-- it was in the beginning. And now, it feels like it's run its course.

RAMESH RASKAR: Yes.

AUDIENCE: And so but there's still photography in the traditional sense of capturing what the human eye sees is fundamental in some way, which is separate from the technique, things like [INAUDIBLE]. So I guess the question that I have is, what is the fundamental of the photographic medium? And in terms of technology, what would be the fundamental technological [? ability ?] as opposed to separating that from kitsch?

RAMESH RASKAR: I agree. I agree. I think the camera, to me, it's just a sensor. It's just a transducer. And people say, wow, if the camera is going to change, fundamentally, it's still going to convert electrons into photons and photons into-- sorry, photons into electrons, and electrons into pixels, and so on. The laws of physics are not going to change anytime soon.

So how we use it, though, it's going to change altogether. And this notion that once you take a picture, that's set, use the best possible optics and sensor so that it captured image and that you can see later is changing. So it will shift. I'm glad you brought it up because that's the very next thing I was going to show.

This is going before that. I'll come to this. [INAUDIBLE] some other interesting images are time lapse mosaics. So again, I sat in my office and took these time lapse pictures. And on the left side, it's daytime. Bright time, it's nighttime. And all I'm doing is just picking up strips of the images from different times of day. And [INAUDIBLE] annoying artifacts because it's on some other exposure. But using a gradient domain technique, you can create a very smooth transition.

AUDIENCE: [INAUDIBLE] cop car.

AUDIENCE: Yeah, cop cars and--

RAMESH RASKAR: Yeah, exactly. It still has those problems. So I don't have as much patience. And I'm only doing it sitting in my office. But it's just a tool that photographers could create, create images that have a very different notion than what your eye will see if you're there sitting in an office. Of course, hopefully, this can be done in Times Square or some really interesting places. And by the way, this one is also catching up now on Flickr, a lot of people who are trying to do this. We did this in 2002. But--

AUDIENCE: So in lots of examples we saw here, the final result is an image like a final master in sound, where you do all equalizing. There is one sound. And lots of techniques now could be also interactive. You could actually go and those will be made. It goes through every part of it, because that is the final goal is to understand it. There is this idea that there is something complex about who [INAUDIBLE]. And it could be interactive as well.

RAMESH RASKAR: Right.

AUDIENCE: So in one sense, the [INAUDIBLE] goal is always to create a new static image or media. The interactive parts would be so interesting.

RAMESH RASKAR: Yeah, I think you're pointing to a very important fundamental, again, constraint we have put on ourselves. That an imaging device should create, eventually, a 2D photo.

AUDIENCE: Yeah.

RAMESH RASKAR: And that's very limiting, extremely limiting. And we will be spending a little bit of time near the end of the semester talking about display technologies, because unless there is corresponding innovation, and research, and products, and services in display, it doesn't make sense to spend a lot of time on sensors. So yeah, the two have to go hand-in-hand. And there are some exciting directions there. So the last chapter of our book talks all about these other parallel developments that's going to change how we-- so for example, we have 60 displayed now.

AUDIENCE: Because even in the simple 2D display, there is this project called Photos Projector. Maybe you know. That's also in this, where you can find any [INAUDIBLE] in time. So it's another way of also exploring this. It's

[INTERPOSING VOICES]

RAMESH RASKAR: Exactly.

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: Exactly.

AUDIENCE: And by taking-- giving the controls to the user, it will be used to empower him.

RAMESH RASKAR: Right.

AUDIENCE: Then just to one final comment representation [INAUDIBLE].

RAMESH RASKAR: Exactly.

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: Exactly. So navigating through photos is a great way. But at the same time-- I love this process. At the same time, we want to think about something that scales.

AUDIENCE: Yes.

RAMESH RASKAR: And build it so people can use it.

AUDIENCE: Yes.

RAMESH RASKAR: So that's another challenge. So let's shift. I'm glad you brought it up. This is the latest fad on Flickr. I think, yeah, the HDR, it's reaching its-- it's bottoming out now. But this is tilt-shift imaging, where this looks like a tabletop toy scene. But it's actually taken from hundreds of meters away. This is in Rajasthan, the city of Jodhpur, the Blue City. And that's when you haven't used the tilt-shift class.

So in the basic principles, you want to create-- instead of making-- keeping the lens, and the image plane, and the plane of focus parallel to each other, if you tilt the lens with respect to the sensor, then it turns out the plane at which things are in focus, the plane of focus, also tilts. And this is based on the shift-tilt principle.

And credit this in detail when we come back to optics and light [INAUDIBLE]. But I just wanted to bring this up because it's fun. And you can play with it. All right. So let's talk about some other things. So illumination. You can use it in very interesting ways. Here's the project, I believe, from Georgia Tech, where they created an anti-paparazzi flash.

[LAUGHTER]

And as you can see, the way it works is the paparazzi will take a photo of a celebrity coming out. As soon as the flash goes off, it's detected by some electronic device. And it will blast more light so that what the paparazzi will get in the camera is some blown out photo.

How does it work? You can-- so let's say this is-- let me make sure I understand. So it comes out a traditional camera. Especially a [INAUDIBLE] camera is actually a retroreflector. I'll explain that in a minute. So if you take a flash photo, especially a cell phone camera, then it appears as a bright spot in the flash photography.

So what we're going to do is this guy here is actually-- it's going to be a camera with a ring of LED lights, which is this one here. And right next to it is going to be a projector. So this is mounted in the ceiling, a camera with LED lights and a projector. Now these LED lights are on all the time. And a paparazzi's camera will appear as a bright spot because it's a retroreflector.

And this projector then, which is right below the mounted camera, will turn on the lights, turn on some pixels that are pointed towards this paparazzi. And so basically, you'll always see this very bright light, bright spotlight, being put on [? hand. ?] At the same time, the rest of the scene is going to be dark because only those pixels of the projector are being turned on. And that's why your camera, when it takes a picture, where it will just see this really bright source that's blowing out the rest of the scene. Yes?

AUDIENCE: What about surveillance cameras? We don't want to bomb them?

RAMESH RASKAR: So surveillance cameras are-- what's the question?

AUDIENCE: I--

[LAUGHTER]

Are they-- if, for example, we want surveillance cameras to just monitor that region, and then we have this device there that bombs every camera that it finds, then probably we are not capturing any information.

RAMESH RASKAR: Yeah, exactly. All right. So the point is, can you--

[INTERPOSING VOICES]

RAMESH RASKAR: --defeat surveillance cameras [INAUDIBLE]? Yeah, there are-- we will learn a lot of interesting ways you can beat traffic cameras or those cameras in this class. But that will all happen at the very [? chance. ?]

[LAUGHTER]

[INAUDIBLE]. So what is there to reflect? And we'll look at those. Can you guys all see this over here? [INAUDIBLE]. So if you have a traditional surface, like a wall, light comes in. And it gets reflected in our direction. And you've got a diffuse [INAUDIBLE].

If you have a mirror, then light comes in and gets reflected symmetric around the [INAUDIBLE]. But most surfaces, like this surface here, over here, light comes in. And it doesn't reflect in a uniform way. And it doesn't behave like a mirror. It's somewhere in between. So you get a bright spot. But you also get some other [INAUDIBLE] and so on. Is that clear? So diffuse, light comes in, gets tilted in all directions. Mirror goes in one direction. And a shiny surface is somewhere in between.

There's other surfaces where light comes in and it reflects back in the same direction. And same surface, the light comes in and reflects back again to the same place. And this is retroreflective. And this is very useful material that you can use in many cases. Anybody know where this is used?

[INTERPOSING VOICES]

RAMESH RASKAR: The back of your backpack [INAUDIBLE]. That's reflector of the [INAUDIBLE].

AUDIENCE: [INAUDIBLE] system [INAUDIBLE].

RAMESH RASKAR: Oh, that's right. [INAUDIBLE], yeah.

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: [INAUDIBLE] on same principle as the camera and the signal [INAUDIBLE]. So human eyes also reflect. And we'll see what happens. So this is a principle of retroreflection. How it may work, there are multiple ways you can make it happen. You can just have a so-called [INAUDIBLE] situation. If I put a [INAUDIBLE], which is the mirror, then it comes out no matter which direction light comes in. It goes back in the same direction. It comes from here. And here, it goes back the same direction.

So [INAUDIBLE] is a very useful retroreflector. In fact, if you go to many shops, especially tiny shops which put mirrors on their walls to make it look like it's much larger [INAUDIBLE] reflections, and you stand at the corner of such [INAUDIBLE] shops, you look at the corner, you will see your own mirror image, which is strange because they say this is a shop. And there's a mirror here. And you're standing here. You'll see your own reflection here in this mirror. And you'll also see your own reflection here in this mirror.

But you'll also see you have one image here in the corner. And as you move around, this image will move with you. This image will move with you. But this image will always be in the corner. It's retroreflection. I look at the corner, I always see myself. So I'm surprised we don't have mirrors like this in our house so that I don't have to actually go in front of the mirror. I could be anywhere in the room. And I will still see myself no matter what I do. So you could build a mirror like that. It's just that you [INAUDIBLE]. Yes?

AUDIENCE: Can you use it also for measuring [INAUDIBLE] laser?

RAMESH RASKAR: Yes.

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: Exactly.

[INTERPOSING VOICES]

RAMESH RASKAR: [INAUDIBLE]

AUDIENCE: Very good angles [INAUDIBLE] for

[INTERPOSING VOICES]

AUDIENCE: Yeah.

RAMESH RASKAR: Yeah, so that's one way of doing it. Yes?

AUDIENCE: Is [INAUDIBLE] reduction also required? Because rhetorically--

RAMESH RASKAR: Very good point. Very good point. So whether reduction is like [INAUDIBLE], you see-- and the color red is because the chemicals are [INAUDIBLE]

AUDIENCE: [INAUDIBLE] also, [INAUDIBLE].

RAMESH RASKAR: Huh?

AUDIENCE: That could [INAUDIBLE].

RAMESH RASKAR: Exactly. Now both of those are another way of doing it. So you-- so once [INAUDIBLE] the other way is--[INAUDIBLE] property of this one is you know how people will say, in the mirror, you get confused. If you move your left hand, your right hand moves. And you move the right hand, the right hand moves.

The [INAUDIBLE], that doesn't happen. You can move this hand [INAUDIBLE]. You can move this hand so your image, it's not clear [INAUDIBLE]. Is there a shop around here with mirrors like this?

You use the [INAUDIBLE]. All right. So other one is false. If I just take a shiny-- this is the last [INAUDIBLE], actually. Night comes in. It reflects because of this refraction. And then, it reflects again because, of course, we need another reflection. There's a refractive index here [INAUDIBLE]. And then, it goes back out. And then [INAUDIBLE].

So that's how a glass bead-based retroreflector would work. And then, of course, you'll have a bunch of these. So you can [INAUDIBLE]. All right? And this is exactly how a rainbow works. So you see a rainbow after you've had this rain. This is how a rainbow works. If you ever see a rainbow with maximum-- most vivid colors, what conditions you are satisfying? This is for the sun. And this is for the high-humidity here. What's the [INAUDIBLE] condition [INAUDIBLE]?

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: [INAUDIBLE]

AUDIENCE: [INAUDIBLE], yeah.

RAMESH RASKAR: So this is the sky. The sun is just setting. You are here. And you're going to see it exactly in the opposite direction here. So the rainbow is here. So very common. You would go to some place with a waterfall. And you want to see the rainbow. In case of a challenge, you can see it sometimes. You don't see it sometimes.

All you have to make sure is that the sun-- so usually, it's high enough. You can see the rainbow. Because you can imagine if the sun is pretty high in the sky, you'll never see a rainbow because it's occluded by the surface of the Earth. But when the sun is low enough, you will see a rainbow.

On the other hand, you just have a mountain, then even in the daytime, you could see the rainbow if the [INAUDIBLE]. The lowest point by this are allowing you to see the retroreflection. And we're coming to, why this rainbow? Because the refractive index for different times [INAUDIBLE]. So that's why we see [INAUDIBLE]. So it's all fascinating [INAUDIBLE], retroreflection.

So in case of, why does the human eye have red eye or a cat has these bright spots? It's the same reason. So all you want is [INAUDIBLE]. Light goes in, comes back in the same direction. So if you have now a [INAUDIBLE]. So now, if you have, let's say, a camera for now. And human eye was almost similar [INAUDIBLE]. And there's a bright spot, bright light. I'm going to stand right next to it. Light goes in. And this gets focused. That's the point.

And as you can imagine, if you're a sensor, it actually has a shiny [INAUDIBLE] in front of it. If you look at a sensor, you'll realize it's pretty shiny because [INAUDIBLE]. Light goes in and reflects. And no matter where light comes out from, because of the geometry of the light, you can go back to the same spot.

Now [INAUDIBLE] for the focus, you do not see it because [INAUDIBLE]. But if the point was in sharp focus, on the sensor, it will reflect back. And it will come back in the same place. And so this is the same reason why for a human eye, again, in a situation like [INAUDIBLE], it reflects and comes back in the same direction. [INAUDIBLE]. So the reason why I tell you, what's the new strategy for removing a red light? What should you do?

AUDIENCE: Flash phase or [INAUDIBLE].

RAMESH RASKAR: Flash out. Or if you have a cheap camera, where you--

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: [INAUDIBLE] camera. Because you're not looking at the camera, you have-- the image that we formed is forming something that's made of the light [INAUDIBLE]. And so you're not referring back to the camera.

AUDIENCE: So the anti-paparazzi system will also blind everybody [INAUDIBLE].

RAMESH RASKAR: If it was--

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: If the--

[LAUGHTER]

If the city-mounted light was omnidirectional, then that would matter. But because the projector had constrained light only at [INAUDIBLE] points [INAUDIBLE] this point.

[INTERPOSING VOICES]

RAMESH RASKAR: Yes.

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: Or this camera. We don't want to [INAUDIBLE].

AUDIENCE: I think the point JD was bringing up is that human eyes are also retroreflective. So if you look at a spot, it will potentially flash you.

RAMESH RASKAR: Is that what you're saying?

AUDIENCE: Yes.

RAMESH RASKAR: Yeah, so--

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: It's true. It's true. So this is among the rules.

[LAUGHTER]

So just don't go there with [INAUDIBLE].

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: So also, you know that [INAUDIBLE] are a very technical environment. Usually, [INAUDIBLE] have more problems with [INAUDIBLE] don't have a problem with [INAUDIBLE]. And that's just because of the pigment and so on. But you're right, that If the system works really well, it will also blind all the [INAUDIBLE].

[LAUGHTER]

AUDIENCE: So if you have the masks, something to put into your lens, then this will seem, obviously, [INAUDIBLE].

RAMESH RASKAR: Oh, yeah, that's the next [INAUDIBLE], how to beat [INAUDIBLE].

AUDIENCE: And

[INTERPOSING VOICES]

AUDIENCE: You can use the flash.

[LAUGHTER]

Use a camera with a high-ISO [INAUDIBLE].

RAMESH RASKAR: Yeah, there's a lot of ways to get around it, always. If you want to have a very nice discussion on how to change your license plate so that the--

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: --high-speed-- whatever, the--

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: --speeding cameras will not be able to see it. You ought to buy me a beer.

[LAUGHTER]

All right?

AUDIENCE: Yeah.

RAMESH RASKAR: You're up for it?

AUDIENCE: Yeah.

RAMESH RASKAR: You're over 18?

[LAUGHTER]

AUDIENCE: Yeah, 21 [INAUDIBLE].

RAMESH RASKAR: I did not say age. All right. Good. So before we take a short break and go into the illumination, more discussion, I just want to give you the final projects you could be working on. Remember, we are really here to do something that's cool as well as novel. So many times, I'm going to bring up a list of the projects that are not cool. All right? And again, no offense to somebody who might be working in a similar field. But just, let's be honest. Let's do something nice.

So here are some suggestions for types of fun projects you could be doing. You have beautiful user interaction devices that are always fun. You start using a 2D sensor camera. Maybe use the [INAUDIBLE] camera for the finished camera, which can be, by the way, created from a flatbed scanner. You can buy a flatbed scanner for under $100. And it's actually a multithousand frame rate camera. You can just hold it in one place. And if you walk in front of it, you'll basically create a photo finished camera.

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: Yeah, there are a lot of issues. But we'll help you on that. We'll help you on that. Yeah, like Dino was saying, it's not something you can just buy and just plug it in. You have to get your hands dirty in [INAUDIBLE]. Or just use photodetectors, single-pixel cameras. You can do a lot of interesting things with it. You can include some interesting illumination.

Capture the invisible. It's always my fascination on, how can we capture something that cannot be seen with the naked eye? So maybe bring some tomography machine that can see inside the body, some structure like 3D scanning or fluorescence. And we'll see that experiment here just in a minute.

And this is a question you were asking earlier. Are there cameras in other domains, electromagnetic, or audio, or resistant. So how about an audio camera, or a magnetic camera, or a capacitive camera? So we won't be discussing it a lot in the class. But I think it's a great way to do a final project. Thermal lab camera, we can help you. Maybe a thermal lab camera that detects emotions.

Multispectral camera, cameras that can distinguish between two very similar colored objects. There's a lot of us interested in distinguishing camel from sand. So can you create some mechanisms so that two very similar looking objects can be completely distinguished? There's a lot of market in the golf business, where people want to spot their golf ball on a green background. So you just put this-- you know what to do?

Yeah, they sell it for hundreds of dollars. All you need is a blue filter. If you put a blue filter on the grass, which is green, it looks black. But your ball, which is not green, stands up. So you have a black background. And anything that's not green will really stand out. You can-- there are lots of other businesses [INAUDIBLE].

Illumination. [INAUDIBLE] photography, I think we saw earlier. A lot of fun. All, kinds of, strobing. Nonimaging elements such as gyros, GPS, interaction between two cameras. Maybe there is some lighting communication or Wi-Fi communication between them. Optics is always a lot of fun, camera areas, light fields, portrait aperture.

Maybe try to mimic a vision of one of the animals. Or study. Bring some worms or bring some cats. And cats are, by the way, really beautiful mechanisms of how they work. And we'll have a whole lecture on animal eyes. I think seventh or eighth lecture. So we'll study that.

And time. Timelapse photos, there's so much information in time lapse photos. I wish I could go on Google Earth or Google Street View and it will show me time lapse. It can't be that difficult. They'd have to scale their database only by a factor of 24, which is not that much more, I think. But it'd be nice to see the same place in the daytime and nighttime, and what, kind of, traffic it has, and what, kind of, people it has. Right now, it's very static about its appearance.

Somebody had a very nice idea for time lapse photos for Google Street Map, which is-- sometimes, you don't need a video of what's going on there. But the world, at least man-made world, usually, it will only have a few discrete steps. If there's a traffic light, it just switches between three different colors.

If there's a bridge on the river, that drawbridge, it's either this position or this position. There are a lot of these discrete things that happen in man-made world. So it'd be nice if in Google Street, you can see all those discrete steps, discrete situations in [INAUDIBLE]. You can create this direct global separation. I think we saw that earlier. Create new types of cameras that are over 10-- these are all suggestions for final products.

Mimic animal eyes. Play with photonic crystals. They're are very easy to make now. Photonic crystals, basically, in simple words, these are ordered arrays of materials that have different refractive indexes. In the simplest case, it could be just glass and air. So if you could just create micron-scaled holes in glass, it behaves in very interesting ways. So maybe somebody will play with that [INAUDIBLE] photography and [INAUDIBLE].

AUDIENCE: Ramesh?

RAMESH RASKAR: Yeah?

AUDIENCE: You say it's very simple. How do you do that?

RAMESH RASKAR: By simple, I mean--

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: Yeah, the idea is fairly simple. Actually, when photonic crystals were invented in Bell Labs, they literally took CNC C machines in metal. And they just punched holes.

AUDIENCE: You can get access to that or [INAUDIBLE]?

RAMESH RASKAR: We have a microelectronics laboratory. I think Quinn knows about it. And we can-- I think there's some charge. But I can easily take care of the funding for that. And I think you pay a fixed one-hour rental for it. But if it's a research project, maybe we can even get around that.

So in fact, you can buy now nanomaterials and photonic crystals just online. You can get two-micron beads and six-micron beads-- sorry, two-nanometer beads and six-nanometer beads online. Very toxic. A little bit dangerous. But there are certain varieties that you can just use. So it's a lot of fun to play with that.

And here are some sample projects from last year's class. In our [INAUDIBLE] photography, again, this was the only undergrad in the class. And he won the best award, Best Project Award, from Nokia. Jessie from mechanical engineering did a camera array for particle image velocimetry. And now, it has become his PhD thesis. And he's applying for hundreds of thousands of dollars in grants.

Bidirectional screen was a project by Matt, Matt Hirsch. Again, it has become his master's thesis, SIGGRAPH paper, and so on. [INAUDIBLE] Kermani, in my group, he just looked at the theory, he didn't have time to build anything at that time, but looking around a corner, which is, again, a paper this year. Somebody is building a tomography machine and so on. Lots of cool things.

As you can imagine, last year, the emphasis was a little bit more hardware-intensive because the people who are taking the classes were interested in that. But this year, we have a more diverse crowd here. So I'm expecting projects in just art or photography, beautiful synthesis of images, real-time XCS systems, maybe some different types of scientific imaging, maybe a new microscope, anything of that variety.

And we'll spend a lot of time together. We have four or five mentors assigned. We're working with you on the final projects. All right. So let's take a short break. And the short break, we are going to show you some cool fluorescent demos here. And then, we'll start back in about 10 minutes to talk about other types of image. So here's a big question for photography. 1930s, we had big cameras. The guy had to get under the cloth to take a picture.

AUDIENCE: That's actually a press camera. It's pretty small. And people

[INTERPOSING VOICES]

RAMESH RASKAR: This is more recent. But I'm guessing you have cameras that are bigger than this?

AUDIENCE: Yeah.

RAMESH RASKAR: And there's nothing wrong in having large cameras [INAUDIBLE]. And that has shrunk down to something, this, and this, and $0.20 with all the electronics, and processing, and so on. But when you think about lighting, not much has changed. It has definitely not reduced in size. It definitely has not reduced in cost or convenience and so on.

And in a way, what really distinguishes consumer photography from professional photography is not the camera anymore, but the lighting. So this is a challenge for our community, who we like to think about making everything programmable and easy to use. The same revolution will not happen for illumination.

So we're going to explore that a little bit into today's class, then come back and talk some more in the next class. So when it's all about cameras, we try to make it very smart with the lenses, and different sensors, and new processing. But the light source is still a flash. Maybe it has fancy umbrellas and so on. But it's mostly a flash.

So what we want to do is replace that into a more programmable illumination in a very high-dimensional way. It's geometry recorded for the illumination field in time and color. All right? So some of the earliest examples, and this whole field is called computational illumination, we're going to use computing even in the lighting. And maybe the pioneer was Edgerton, Dr. Edgerton right here. Very famous examples of bullets going through through an apple. And Santiago saying, you have this one or--

AUDIENCE: The three balloons.

RAMESH RASKAR: Three balloons, yeah. So [INAUDIBLE] has beautiful, beautiful pictures. Are they in your dorm room?

AUDIENCE: I've seen one.

RAMESH RASKAR: The same one? Yeah, great. So beautiful pictures. But they were not captured with smart cameras. They were captured with smart lighting. You have an ordinary camera, where the shutter is open for a certain duration. But then, you have a flash that freezes that motion, which, as I recall, was troublesome.

And in this particular case, you have a sequential strobe that captures this whole circle. Nothing smart about the camera. Really smart strobed lighting. And of course, [? Doc ?] Edgerton came up with chemical processes to create very sharp duration light sources. But now, we have LEDs and solid state devices. We can control light down to a few picoseconds or nanoseconds. All this can be done very easily in your house.

So again, this is what distinguishes consumers from professionals. And we look at this step-by-step. And this will be a more technical discussion about what parameters of light we can change. So let's think about, what are the things we can change about light? One is clearly the brightness. What are some other things we can change?

AUDIENCE: Color.

RAMESH RASKAR: Color.

AUDIENCE: The coordination.

RAMESH RASKAR: The cone.

AUDIENCE: [INAUDIBLE] polarizing.

RAMESH RASKAR: Polarization.

AUDIENCE: Coherence length.

RAMESH RASKAR: Go ahead and slant a little bit more exotic, yes.

AUDIENCE: Diffusion.

AUDIENCE: The direction.

RAMESH RASKAR: The direction, yes.

AUDIENCE: Color.

RAMESH RASKAR: Maybe it's not even a single cone, but just a projector. Different directions have a different intensity.

AUDIENCE: Time.

RAMESH RASKAR: Time. So strobing, or duration, or synchronization with the captured image.

AUDIENCE: Relative fades.

RAMESH RASKAR: Relative fades, of course.

AUDIENCE: The lenses on your lighting [INAUDIBLE].

RAMESH RASKAR: For lenses, exactly. Don't think of your flash as just a light source. But put fancy optics or masks in front of them to control, again, direction and so on.

AUDIENCE: You can put inside the object [INAUDIBLE].

RAMESH RASKAR: Yeah, you can change the environment, not just illuminate the environment, but change the environment by putting some interesting lighting inside there. So this is, by the way, another great way to come up with new ideas. And you say, this picture really bothers me. What can I do? And if you want to do research in this area, you ask this question yourself, what are all the ways I can control the lighting parameters? And I'm going to go through one-by-one and see how I can attack them.

And we'll see examples of exactly how that has happened over the last several years. So the simplest one is I can have light or no light. The simplest [INAUDIBLE]. The next parameter is duration, how long it's on or its brightness and so on, its position, its color, using it as a projector, especially angle, modulation in space, modulation in time, and sometimes just natural light, just time lapse, which we saw. All right?

So we'll just look at a few projects to get us motivated. And we saw this one last time, a multiflash camera, where we're really trying to solve a new problem. If I want to tell you what's inside my car, I can just take a photo and send it to you. But when car companies want to do the same thing, they hire artists. So the question is, why do we hire artists to draw something that can be photographed? Yes?

AUDIENCE: They might know what's more important or less important [INAUDIBLE].

RAMESH RASKAR: The semantics is very important, yes. Yes?

AUDIENCE: [INAUDIBLE] reflection, so like edges.

RAMESH RASKAR: So yeah, reflections are annoying. And they don't really add any information. And edges just felt more important.

AUDIENCE: In that picture, so the central elements are highlighted.

RAMESH RASKAR: Exactly. The hand is brighter than the rest of the car. Is that what you mean?

AUDIENCE: Yeah.

RAMESH RASKAR: Yeah.

AUDIENCE: Some unnecessary wires or [INAUDIBLE] can be--

[LAUGHTER]

RAMESH RASKAR: Yeah, all these things, it's just clutter. It's not critical to explaining what's in the car. It just looks wonderful. So yeah, unnecessary shadows, clutters, too many colors as opposed to highlighting the shape, and just marking what's moving, and using very simple, basic colors. Yes?

AUDIENCE: [INAUDIBLE] strategy [INAUDIBLE]?

[LAUGHTER]

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: There are some other names for it.

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: Not for [INAUDIBLE]. So imagine if you can just build a camera that gives you an image on the white as opposed to black. We are not trying to put the artists out of business. But we are trying to create tools so that they don't end up time rotoscoping and drawing the lines. They get all the line maps very quickly. And then beyond that, the creative process starts. So get rid of this tedious task of finding the edges, and marking, and so on, like all the magic scissors and so on.

So of course, the first solution would be just take the photo and try to find intensity edges. It turns out it doesn't work very well. And this is the problem you face in XCI all the time. You have some gestures with your hand. We might have some challenging background lighting. Then a typical method is to maybe do some edge detection, color detection. And you just hope that they are not-- the lighting is just right when you're showing the demo and you have matched-- controlled the background just enough so that everything works out.

Or you can be smart about it and use-- distinguish within reflectance edges, which are edges between different materials, and distinguish them from depth edges, which are real geometric edges. So these are all intensity edges. And these are all just geometry edges. So imagine if I could take a photo of this and get this out. It would be much easier for me to write an interactive system that's based on it.

AUDIENCE: Well, this is really like a computer-based question, actually. The example with the car [INAUDIBLE] maybe a professional meeting because a human being knows what to abstract

[INTERPOSING VOICES]

AUDIENCE: --to normally emphasize [INAUDIBLE].

RAMESH RASKAR: Yes, it's multiple goals. So one goal is a diminished reality--

[LAUGHTER]

--trademarked by--

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: Sorry?

AUDIENCE: [INAUDIBLE] the internet.

RAMESH RASKAR: All right. So [INAUDIBLE], who's a scientist in our group, has a very interesting way of putting this. He says, photography, it's well-known. Photography is the art of exclusion, de-emphasizing things that-- the photographer makes a decision on what to de-emphasize either by using focus or by cropping it and so on so that the photographer can convey to the viewer what's most important.

But what we're doing computationally now is adding another level of exclusion. In this case, we're excluding the intensity edges and just keeping depth edges and all these other things. So computationally, we would extend the concept of exclusion. So one could be for nonphotorealistic rendering for creating cartoons. One could be for XCI. And there are lots of other things. Right now, this is being used in Mitsubishi products for some really bizarre things.

So we saw the idea last time. You get the slivers of shadows. And by analyzing the shadows, you can continue-- compute the depth discontinuities. And some people like to call it slivers. Some people like to call it occluding contours or shape boundaries. But they're not so precise. And depth discontinuities is what we're really talking about.

So when I take a photo, then the depth of this pixel and depth of the pixel on the other side of this screen has a [INAUDIBLE] discontinuity. And that's really what we're talking about as opposed to slivers, where it's usually about just the external part. Well, if I put my hand over here, this is still a depth discontinuity from my hand to my body. So I would like to capture that.

And shape boundaries is also not very precise. So depth discontinuity is really what we're talking about. And imagine if this is in the Sony EyeToy or the Microsoft Natal. Then if you have a depth camera, if I put my hand really close to my body, it cannot distinguish the depth with respect to the camera of my body versus my hand. But with this camera, I can still continue to detect that there's a shadow that's created from that.

AUDIENCE: How about that laser from--

RAMESH RASKAR: Sorry?

AUDIENCE: The laser projector camera?

RAMESH RASKAR: Yeah, so actually, the Microsoft Natal uses this PrimeSense sensor, which is not time of flight, but based on triangulation. But anything that senses depth as opposed to depth discontinuity will have the same problem because, as you get closer and closer, you'll not be able to detect that.

AUDIENCE: If you were testing for a piece of paper, it seems pretty good.

RAMESH RASKAR: It was very good. Yeah, it was very good. Yeah, so if it's a really good depth-sensing camera, then you're all set. But it has poor resolution. And it's a much more complex device. So again, shadows to the right, shadows to the left, and so on. But then, look at the shadows. They are not just one-pixel-wide. Depending on the depth difference, they could be very wide or very narrow.

So you want to create an output that's exactly one-pixel-wide. So how does this work? So before we go there, I guess, is there intensity in this? These are [INAUDIBLE]. And we can just put that together and create a cartoon in real-time. In fact, we demonstrated this. So yeah, this is another example, my old '93 Honda Civic. And this is what you will get if you use the intensity detector. This is what you get from the four flashes.

And you will see the Honda sign here. That's barely visible here. That's because the Honda sign has a relief. It's a height field. It's a geometric rather than texture. And all these scratch marks and rusting is just texture. It does not contribute to the geometry. And if you try to locate the spark plugs or the dipstick, it's barely visible here. But again, here, you can see it right there.

So the shapes are what we're really looking for. And we've got the four images, input images, just four images. You can see to the naked eye, they look identical to a naive observer. But you look at the shadows. Here, the shadows are to the right of these pipes. Here, the shadow are to the left of these pipes. Here, the shadows are at the top. And here, the shadows are at the bottom. And by analyzing the shadows, you can find the [INAUDIBLE]. Yeah?

AUDIENCE: In practice, honestly, the farther continuous from 12 feet away, it's not as effective because your flashes are pretty close to the

[INTERPOSING VOICES]

RAMESH RASKAR: Right. Exactly. So we'll talk a little bit about what parameters you are to choose to get an optimal performance. And yeah, there's definitely a sweet spot where it works in the system. Some more examples here. And I just want to describe to you very quickly the geometric parameters that make it happen.

But we were showing this live at SIGGRAPH. And you can stand in front of this camera, where every iconic fourth frame had a different flashlight going off. They put in the lead-in. You can stand in front of it. And it's a cartoon. And I'm a big fan of the A-ha video from the 1980s, "Take On Me."

[LAUGHTER]

You remember that?

AUDIENCE: Yeah.

AUDIENCE: Wow.

RAMESH RASKAR: I thought I was too old to appreciate that. But so in the A-ha video, there's this very beautiful effect where on one side of the glass screen, the world is cartoon. And the other side, it's real. And so when we were showing this, it goes on for four days, after the end of the first day, people started saying, oh, this reminds us of the A-ha video, the "Take On Me" video. And I said, yeah, that's really true.

So we got really sick of those comments. And on our demo, instead of calling it-- we had some really boring technical name. We said, this is the A-ha demo, "Take On Me" demo. And we had it in big letters on a huge screen. And then, on the second day, the curator of the show came to me. And she introduced me to this guy. And she said, this is, I forget his name, David Patterson. This David Patterson, do you know him? I said, I don't know him. He said, he was the music video director of A-ha.

[LAUGHTER]

And so I said, wow, that's great. We're really inspired by your video. He looks up on the screen. And our demo was inside a closed quote. And they're showing the live output of that on the big screen. And he said, what are you showing there? I said, this is live. We can go inside. And this is being computed in real-time. And he said, that's impossible because when we were doing it in the mid-80s, every frame took them a whole day--

[LAUGHTER]

--to rotoscope and so on. And so we were excited. Patterson is here. So he comes inside. He acts very cool. He looks right there. He looks at the images. And we take-- we get very excited. We take pictures with him. He leaves. But after 1/2 an hour, he brings his son with him.

And he started explaining to him. His son is two or three years old. He said, wow, remember in the 1980s, I worked on this video? These guys are doing it in real-time now. And we said, welcome. We're pretty happy you brought your son. You must be excited. After a couple of hours, he brings his wife.

[LAUGHTER]

And then, it just goes on all day long. He just keeps bringing people to show them how this works. So that was a high-point of that [INAUDIBLE]. So how does it work? So you have a camera. And you have your flashlight, which is shown as P here. And then, because of the parallax between the lights and between the lens and the light source, you're going to cast a shadow of this object.

If the flash is to the left, the shadow is going to be cast on the right. And if you just freeze the rig from the light source to the object to the shadow, it's going to be projected in the image as this particular vector. Now what's interesting is that it turns out we need at least three light sources. You don't have to use four. But you need at least three light sources.

And let's say you have three light sources, P1, P2, P3. And the image of the light source is denoted by E. So the shadow, it turns out, lies along a so-called [INAUDIBLE], those of you who are familiar with the [INAUDIBLE] geometry. And as long as we make sure that for any given silhouette, any given depth edge, there is at least one light that's on one side of that edge and there's at least one light that's on the other side of that edge, we can guarantee that at least in one image, you will see a shadow. And at least in one image, you will not see a shadow.

And while being able to compare-- so out of four, in our case, at least one of them will have a shadow. And at least one of them will not have a shadow. So by guaranteeing that, we can analyze the four images and compute how that works. So here's a very simple example. It flashed to the left. So the shadow is on the right. Here, the flash is on the right. So the shadow is on the left.

And all you do is take these two images, find the max operator, take the max of every pixel. And this is what you can do with HDR Shop. I don't know if you can do it with Photoshop. Can you just take two images in Photoshop and find the max of the two? At every pixel, I want to compare the two pixels. And I want to take the maximum of the two.

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: You can do that?

AUDIENCE: Well, I learned that there are filters that you can do that with one layer and the layer behind it and [INAUDIBLE]. I don't know if it's exactly that.

RAMESH RASKAR: Yeah.

AUDIENCE: But [INAUDIBLE].

RAMESH RASKAR: Exactly. But nobody cares about doing nice, simple mathematical operations. So HDR Shop is great for these things. All these things, you can do it in HDR Shop in 15 seconds [INAUDIBLE].

AUDIENCE: Another [INAUDIBLE] introduced it. But [INAUDIBLE] image processing, ImageJ is really a nice--

RAMESH RASKAR: ImageJ?

AUDIENCE: ImageJ. It's Java-based and all open-source. So if you want to take a look at the code, it's all there.

RAMESH RASKAR: Excellent.

AUDIENCE: And also, you can script all of these functions with a lot of images using JavaScript--

RAMESH RASKAR: Excellent.

AUDIENCE: --which is really useful.

RAMESH RASKAR: Just send a link to the class or to Sam so it'll go in the notes.

AUDIENCE: Cool.

RAMESH RASKAR: ImageJ. I know there's OpenCV and all those things. So I'm sure you'll use them. In MATLAB, again, it's one-line command, max a, b, a vector, b vector. But basically, one-line code to take a max of two images. In Photoshop, every 30 minutes. So all you do is take the max of the two and take the ratio of this image by the max image, which I call normalized.

And then, we want to divide that. And if you divide it, all the texture goes away. And only the shadows are left. Wherever there was no shadow, you'll get a value of one. The ratio is one. Wherever there's a shadow, you'll get a value that's close to zero. It's not always zero because there's some other lighting.

And now, all you have to do is if you take one scan line here, this is how you plot it. And you can see the shadows very clearly. And same here. In the left image, just scan from left to right. And wherever you see a jump from lit area to an unlit area, it has to be a [INAUDIBLE] touch. In the right image, you scan from right to left. And wherever, again, you see from lit area to unlit area, that's a [INAUDIBLE] touch.

So in every one of those four images, you'll be able to find [INAUDIBLE] touches from different orientations. And then, we can take a union of all these four images. And that gives you a full [INAUDIBLE] touch image. So in this case, for example, all these internal edges are completely ignored. And all you see is silhouettes.

And in MATLAB, that's all there is, 15 lines of code and no parameters. No tuning required. There's no constant that's used anyway. So it's extremely easy to use. You can implement this. You can use it. I'll give it as an option for one of the class assignments so you have a choice to use this. Any questions on this one? Yes?

AUDIENCE: So you said outline. The boundary is only a one-pixel line. But if you actually provide more than one pixel, depending on how thick the shadow is, can we get more depth [INAUDIBLE]?

RAMESH RASKAR: That's a very good point. So depending on how far things are, so here, for example, the shadow is wider than here. And that's because the depth difference is larger or smaller. So you are already right. That thickness of the shadow actually tells you a little bit about the depth difference, not the depth itself, but the depth difference.

AUDIENCE: So you get more 3D information out of it.

RAMESH RASKAR: So you could get a little bit of 3D information as well. Yeah, that would be nice.

AUDIENCE: [INAUDIBLE] capture? So [INAUDIBLE] like a machine in the shop.

RAMESH RASKAR: Right.

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: Yes.

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: They just use a laser scanner, usually.

AUDIENCE: Yeah.

RAMESH RASKAR: Yeah, unfortunately.

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: You can just capture the silhouette. But remember, we are not capturing depth. We're only capturing depth edges.

AUDIENCE: Yes.

RAMESH RASKAR: It's like saying, I'm not capturing intensities. I'm just capturing intensity edges.

AUDIENCE: But [INAUDIBLE].

RAMESH RASKAR: So this work has really taken off. There have been lots of papers that are based on this particular technique. And so people have tried to do [INAUDIBLE]. Some people have tried to do some-- it's still open. It's very new. Or it's some three, four years old. And people are trying to do different color lights. So there's a lot you can do. Question up there?

AUDIENCE: Could you actually capture depth? Or at least the difference between different edges so you can study the [INAUDIBLE]?

RAMESH RASKAR: If you can process the shadow width. But remember, it's not going to be as robust, because if you look at this plot, you have to estimate how wide this region is that's shadowed. So if you can do that fast enough, then yes, you could do that. So it's not-- in certain conditions, maybe it's possible.

For skin, it's very easy because the shadow color is not going to interfere. If something was black in the scene, then that could be detected as a shadow. But in this matter, even if the object is black, it doesn't matter. You'll still get very nice edges. But if you try to estimate the shadow width, then you have a little bit of [INAUDIBLE].

AUDIENCE: Again, all of these techniques assume that you have one [INAUDIBLE] image, which could have [INAUDIBLE]. You can-- then this one--

RAMESH RASKAR: Hey, now you're thinking like a researcher. Yeah, now we thought about all the ways you can change the lighting parameters. Now you're saying, in addition to that, can we change camera parameters and do something more? That's the thinking I want you to have in this class.

AUDIENCE: Yeah.

RAMESH RASKAR: Yeah, always take an idea, x, and think about how you can do the next x. And I posted some slides on how to come up with new ideas on the Stellar webpage. If you're inspired by an idea x, how do you come up with the next idea? And then, there's a systematic process of how you can come up with great ideas.

And also, the same slides tell you, if you come up with a great idea, whether to decide whether to pursue it or not. So I'm curious about your comments. It's just a work in progress. I have been putting it together over the last several months. So again, that allows you to do this in real-time. What are some other things people are doing? You take a flash photo. The person is very brightly lit. The background is not so well-lit. You take a no-flash photo. What has changed in the two?

AUDIENCE: [INAUDIBLE]

RAMESH RASKAR: She didn't blink. Remember, this part of [INAUDIBLE] flash. But anyway, that's a different point. What information can you recover from this?

AUDIENCE: You can separate the foreground from background.

RAMESH RASKAR: You can separate foreground from background because the foreground is well-lit. But the background doesn't change. If I just take the ratio of the two images, it will look something like this if I do one minus the ratio. So the background hasn't changed. And the foreground has changed dramatically.

So this particular paper is called flash mapping. As simple as that. That was the idea for a SIGGRAPH paper in 2006. They went a little bit beyond that and just said, if we just take pure ratios, then you cannot get the strands of the hair and so on. So they used some gradient domain techniques, some graphical techniques to solve this mapping equation of, what's foreground and what's background? And they can also detect these very subpixel features, strands of hair.

And then, of course, you can take that and replace the background. So it was mostly well-lit. It does pretty well here. There's some small artifacts. But it looks pretty good. So just by changing the light, also, this presence and absence of light, you can create some really interesting [INAUDIBLE] or interactions.

AUDIENCE: It's the same technique with a flashing [INAUDIBLE] video.

RAMESH RASKAR: That's a great idea. So you could do alternate frames. And you won't-- it won't be disturbing for the user. And you can just distinguish foreground from background. So very simple examples. We'll progressively become more and more complex, I guess, here. But let's stop here for today. And we'll talk about all these other cool things next time.