**KRISTEN:** So with that, I am going to turn it off to our first keynote speaker, Kris Clark. She also works at Lincoln Laboratory with me, but in a completely different field. She's going to talk about space cameras.

**KRIS CLARK:** So as Kristen said-- I'm also Kristen, but I go by Kris-- I work at Lincoln Laboratory. And I want to say that this is an amazing program. So first, how many of you have ever done a program like this? Like an engineering kind of thing for girls. Come on, way up. I can't see that. OK, cool. Now, how many of you are freshmen? Sophomores? Juniors? Seniors? All right, no seniors. They're all busy doing college applications.

All right, so let's get started. So today, I'm going to talk a little bit about me, just because we're kind of looking at what makes an engineer. It can be all over the map. So there is no one key picture of what an engineer looks like, or what a scientist looks like. Then we'll go into a little bit about just really basic stuff, like what is a camera? What are the key components of a camera? And then what can cameras do?

And then specifically I'm going to tell you about the program I'm currently working on. It is a space camera looking for as exoplanets. So I'll tell you a little bit about the specifics of that, and I have some kind of cool animation that they did for me to show you the orbit, and all that sort of stuff. So stop me, raise your hand. Questions, you don't have to wait till the end or anything. So just speak up. Raise your hand. Get my attention.

So how I got here. So you guys all know, this is Massachusetts. I did not stray very far. I was born in Worcester in the center of the state. I moved to Billerica, Mass when I was two with my family. I went to Billerica Memorial High School. Then I went to MIT for undergraduate, then to Tufts for graduate school. So it's kind of this circle. I never went more than 50 miles from home. And ended up at Lincoln Laboratory. I've been there for the last 12 years working on space-based optical systems.

So I have three brothers. Two of them are also techie geeks. One is a lawyer, so he's kind of the odd man out. But the only time really that I left the country was to be an exchange student for a year in high school. And other than that, stayed very close to home. So there's tons of opportunities right in your own backyard for being an engineer.

All right, so now I need some audience participation. What is a camera? Anyone want to take a stab at just kind of a general definition of a camera. Or even just if you're not really sure how to define it, maybe just describe what it does. That's a good way to start.

**AUDIENCE:** A device that takes photos.

**KRIS CLARK:** Good, good. Device that take photos. Anybody want to add to that? Like a key piece of information you can think might improve the definition for if you needed to describe a camera to somebody.

**AUDIENCE:** Light really affects how the photos [INAUDIBLE].

**KRIS CLARK:** Light affects how the photo is taken. Is that what you said? Yep, so light is very key. That's pretty much what we're trying to collect. Anybody else want to add to the definition? Let's see, this is kind of a generic definition. A camera is an optical instrument for recording or capturing images. So if you look at that definition, really there are two basic components you need to a camera. Does anyone want to take a guess at one or both of them? What's the first thing you have to do when you want to take a picture?

All right, I'll give you this one. Somehow you have to collect the light, right? So focus your energy. It can be visible light. We'll talk a little bit more about other types of energy. But once you have that light where you want it, what's the next step? It's there, but what do you have to do to get a picture?

**AUDIENCE:** Have something record it?

**KRIS CLARK:** Exactly. So you need a detector. So basically two components. You want to get the light for whatever you're trying to image to a particular place. And then you need some sort of device-- old school, if you're old school like me, you've seen film cameras before. You took some of those apart. So film was the detector. Now, it's much more the digital age. You've got CCDs and all sorts of digital imagers. So those are basically the two things that you have to do for a camera. And then from there, sky's the limit. There are so many different types that you can do.

So I thought I'd start really simply. Has Anyone ever heard of a pinhole camera? Anyone ever built a pinhole camera? All right, so what's the basic premise? Do you remember what the idea is behind a pinhole camera?

**AUDIENCE:** Yeah, you just put like little holes in a box.

**KRIS CLARK:** Yep. So you have-- let's see if I can get my little pointer thingy to work-- a tiny, tiny hole in a dark box. So there's not even a lens in this camera. But that tiny, tiny, tiny hole is the first half of what you need for a camera. Something to collect the light. Now the problem with a pinhole camera, the tiny, tiny hole can't collect much light. But it does limit very specifically that light from a particular point in what you're looking at can only get to a very specific point on the inside of the box. And so basically, that's your limiting light collection, and the back surface of the box is your image plane. Now, you can't really capture it, because it's just the back of a box. But you can look at it, and it's there if you want to see it. So very, very primitive.

So if we get into some things that you guys see every day, and you probably don't really think a whole lot about how they work. But who would have guessed how many components are in that little tiny phone camera? That's a lot of stuff. There's like six lenses before you even get to your detector image. So lots of lenses are used. And we won't talk specifically about lens design. But basically, the fancier cameras have gotten-- you've noticed, iPhone cameras always tell you, now our image quality is improved from iPhone 4 to iPhone 6 by whatever percent. It's all about how well you can correct the light that you're trying to collect and get it in the spot where you want it to be. And that takes more and more lenses. So that gets more sophisticated.

And then you have your software for image processing. So you can play around, like when you post-- I'm way too old for this-- but on Instagram and Twitter, you can do it color filters and make it look kind of different. That's all in the image processing, which you guys will get to do.

Now, I like the eye as an example, because you've been using this camera since you were born. And pretty much you have a lens. It focuses the light on the back of your eye, which is called the retina. That's your detector. And then your brain processes that information from the retina. So your brain really is the image processing software.

And I don't know if you guys knew this, but if we go back to-- what do you notice about the image of the tree in the pinhole camera? It's upside down, right. When your eye lens focuses on the back your retina, the image is actually inverted as well. Your brain fixes that for you. So this is kind of a funny thing, like you're looking at it. Your lens actually focuses it upside down, but your brain knows that up and down. So kind of an interesting built in image processing.

So can you guys think of any other examples of cameras that you use kind of everyday? Or maybe not every day, just specific ones you've heard of maybe for other applications. You see a camera somewhere else that you go during the day. Or let's see--

**AUDIENCE:** I guess a camera for medical use, like for surgery so they can see what's inside.

**KRIS CLARK:** Yes, exactly. You guys are going to hear about a really cool medical imaging camera at lunchtime, I think one that detects tumors in patients. So very good example. Anybody got another different example of what cameras are used for?

**AUDIENCE:** Infrared cameras.

**KRIS CLARK:** Yep, infrared cameras. What do those do? Exactly. And that brings us to our next portion. So when we talk about light, is anyone familiar with the term electromagnetic spectrum. You know what that means? Can you describe it a little bit?

**AUDIENCE:** It's the frequency-- it's the different scale for the light [INAUDIBLE].

**KRIS CLARK:** Exactly right. So most of the time when you say light, you think of visible light, right? What we can see. But really, the electromagnetic spectrum defines a really large range of basically electromagnetic waves. And this very small region-- and we kind of define this by wavelength, how long is the wavelength of the light? Most of the stuff we work with is in this very small spectrum.

But it branches all the way out here to radio frequencies, where a wavelength is the size of a building, all the way out to like gamma rays, where a wavelength is like atomic size. So the big reason probably that we focus so much on visible, that's where our eyes work. That's where we learned everything from the ground up of how imaging works, because we didn't have CCDs. We didn't have film a long time ago. We only had eyes and what we could see.

But now there are cameras available, like you said, in infrared. And I have a little picture of that. Take a picture of your dog. So basically it's a different type of camera. It's collecting infrared light, which your eyes cannot see, but the particular lenses that are used to focus this light are specific materials that are used to focus infrared wavelengths. And the detector is sensitive to that range of wavelength as well.

So when we say we need a lens and a detector, it's important to realize that the materials that go into those are very specific to whatever part of the spectrum you're trying to image. So there's an awful lot that goes into it. Some people spend their entire career on visible systems. Some people work entirely in the infrared. There are whole companies-- FLIR System is all about looking for infrared. So their whole business is built on infrared cameras. Certainly medical imaging, right? You've got x-rays. So there's tons of fields, and they can be very specific about what range they're looking at.

So I threw out some other examples. Some of them you guys already hit on. So here's a little tiny camera that you can actually swallow. And people can image things in your digestive tract. It's a little bit creepy to think about, but it works. Certainly if you've been to the airport anytime recently, Homeland Security, cameras everywhere. Does anybody know, there's a specific kind of software that they can use with cameras in the airport. They can do something very specific if you're looking for a particular person.

**AUDIENCE:** Face recognition?

**KRIS CLARK:** Face recognition, right. So that's part of the image processing side of things. There are cameras very sophisticated that can scan whole crowds. And based on a still image of a particular person, they can try and pick out facial features by matching the images. So it's pretty amazing stuff, when you think about scanning through a crowd of hundreds of people and being able to pick out a specific person. So traffic regulation, I know that's a little less exciting. But they take a picture of you if you run a red light.

I've worked on a bunch of programs at Lincoln Laboratory that work to look at various aspects of weather sensing. I worked on one that was made to detect lightning, because lightning causes forest fires. And if you know where the lightning is going to strike, you can kind of be prepared. So very specific uses in weather sensing. And then of course, that brings us to my favorite, space exploration, which is what I'm working on now.

So now over a broad reach of examples, I'm going to talk about specifically the one for space applications. And this is the current program that I'm working on. I've been working on it for about four years. Right from the very beginning when we developed the first prototype camera, and we've refined it since then. So I'll tell you a bit about that. Has anyone heard of it? Because it actually has its own Facebook page, which is unusual for a lab program, because it's completely unclassified, and it has lots of followers. The science community that's looking to use the data from TESS is all over the world. Like the test science community actually meets down the road at Harvard. And they have people from all over Europe. Nobody's heard of it? OK, so not really surprised. But I figure Facebook, you might have happened upon it.

So basically, the goal for TESS-- has anyone heard of Kepler here? So do you know what Kepler was looking for?

**AUDIENCE:** Exoplanets?

**KRIS CLARK:** Yeah, who knows what an exoplanet is? Anybody?

**AUDIENCE:** [INAUDIBLE].

**KRIS CLARK:** Exactly, sorry. Yeah, it's any planet. So that's a pretty large field, because there's only nine-- I still count Pluto. So any other planet that you can think of is called an exoplanet. So something outside of our solar system. So Kepler did look for exoplanets, and it was kind of the first one out there to look and see, well we think there's a lot of exoplanets out there, but let's go look at a specific section of the sky and make sure, before we build lots of other missions to go look for exoplanets that we're kind of right. And Kepler did confirm there's an awful lot of exoplanets to look for.

So along came TESS. TESS's goal is to go up and spend two years basically canvassing the entire sky, looking at specific types of stars-- sort of red, cooler stars-- to identify where exoplanets might be. And we do that, it's very simple, actually. If you have a star, and you happen to be looking at it when the planet's transiting, as it's called-- when it passes in front of the planet-- what do you think happens if you're looking at a star, and you see the light from the star, and the planet goes in front? What do you think happens to the light?

There's a shadow, right? So the light is decreased. And that's really the whole principle behind TESS is looking for those little decreases in the light from the star. Now, it's got some very specific things. You can only see it if the planet is kind of orbiting in front of the star. If it's going around this way, you're not going to see that. So it's a small percentage of chances to pick it up. But that's how we're going to do it.

So I have kind of a cool movie. Let's see if I can get this started. They have some really good graphics, the people at the lab that put this movie together. So this is the general idea. The planet's going around the star. And then at the bottom, it'll start to trace out the light signal. So there's the starlight, and then as the planet passes in front of it, this little dip. Now, what do you notice when the planet passes behind the star? Anybody notice anything interesting? Like when it passes in front, the dip is pretty obvious. But what's the second dip? Anybody get any ideas?

**AUDIENCE:** Well, I just noticed as it goes around the star, the line goes up a little bit.

**KRIS CLARK:** Yep, so somehow we're getting a little more light signal. What do you think that is?

**AUDIENCE:** Reflection from the star on the on the planet?

**KRIS CLARK:** Exactly, exactly. So if you think of a star as emitting radiation in all directions, we're seeing the stuff coming toward us. But as the planet passes behind the star, some of the light that would be going backwards gets reflected forwards, and then you get this kind of increase in your light curve. So this is called the characteristic light curve. So if there were no planet, it would just be pretty much a constant line. And what TESS is doing is looking for these little blips. And they call it periodic, because it happens kind of-- everyone know what periodic means? And the problem is, depending on what star you're looking at, if it's a small planet, what do you think happens to this if the planet gets bigger? Anybody?

**AUDIENCE:** The dip gets deeper?

**KRIS CLARK:** The dip get steeper. Now, we're trying to look for Earth-like planets. And if you think of Earth compared to other planets in our solar system, what size are we? Like compared to Jupiter, we're small. So Jupiter is easy to find, because it reflects a lot of light, it blocks a lot of light. But the smaller you get, and Earth is relatively small, the smaller that dip is. So TESS really needs to detect-- it's about 1% variation in this very bright signal from a star. So that's the challenge for TESS.

Just to show you a little bit about where TESS is orbiting-- and there's a movie, so I won't spend too long in here-- but basically, here's Earth. TESS goes out really far. Like 60 Earth-radius far. Beyond the moon. So they call this highly elliptical. And that's for a lot of different reasons, that primarily it's a very thermally-stable orbit, so the temperature stays the same. And that's one of many variables that go into designing space cameras. You have to be aware of the environment that your camera is going to live in. If you design a camera that works in your laboratory at like 20 degrees Celsius or 70 Fahrenheit, then you transcend it the space where it's minus 80, might not work out so well. So some of the important considerations.

And what TESS does is it has two orbits per month that it stares at a very particular section of the sky. And we have four cameras aligned, so we get a very wide field of view. So we kind of go like this. There's four cameras, and it's almost 100 degrees. And it stares at a section of the sky. And then after a month, it moves. And basically, it scans out the entire sky. So TESS is going to look at not 100%. You can see have a few open areas near the equator. But about 95% of the sky, we'll be looking and watching for exoplanets. So this movie shows it much better than I can describe it.

So you can see the Moon orbiting the Earth. And you can see TESS goes around the Earth twice for every time the moon does. And in fact, the moon-- I don't know a lot about orbital mechanics, but I do know that in the process of getting to that final orbit, there's about three different orbits that it gradually gets further and further out till it gets that final orbit. And it uses the moon and gravitational pull from the moon to hit to get out to that last highly elliptical orbit. So there's a whole lot of interesting science just to get TESS where it needs to go.

So now that TESS is on its orbit, you'll watch. And that outline here, that's the field of view of each of the cameras. So there's four cameras in a row. And it scans out. That's one month at a time that it's scanning out. Now, what do you notice about this part?

**AUDIENCE:** [INAUDIBLE].

**KRIS CLARK:** Yeah. So this is what we call the continuous coverage zone. So in the attempt to see the entire sky, there's going to be some overlap. So basically at the poles, we see almost full-year coverage. Now we're going to the Southern hemisphere, this is year two of the mission. Same thing, we're going to scan out the entire sky. And we get almost full, continuous coverage at the poles. And so not by chance, the follow-on mission. Has anyone heard of James Webb Space Telescope? It's looking up here.

So one of TESS's goals is to provide basically a catalog of just thousands of places to go look. Say, go look at this star, we think there's an exoplanet there. Than James Webb doesn't have to spend a lot of time looking for them. It knows exactly where to look. And James Webb is going up there to-- I have the picture. It's a little bit further. So James Webb is going up there and is going to have a target planet, and go look at the atmosphere of that planet. So TESS is really just designed to find planets. It can't really characterize planets. James Webb can go up and look at the atmospherics of the planets in question and determine is it really like Earth? Is it hotter? Is it colder? You know, what's the atmosphere?

All right, so since you guys have already ripped apart cameras and are going to be building your own, I figured I'd show you kind of the insides of the TESS camera. So we identified our two key pieces. Now, this is basically a section view. So there's an awful lot of stuff going on in there. But basically, this whole back end section is our detector. This front end section is our lens. And anybody have any guesses at some of the stuff you can see in the back behind the detector? Anybody recognize anything back there? Because you're going to see some of this stuff a little bit later.

So detector's pretty much made up-- you have your CCD, right? That's your silicon active area. But you need some electronics behind it, too, right? So you guys are going to see that when you build your Raspberry Pi camera. You can see the electronics that actually pull the image in, and then you're going to do your signal processing. For TESS, that's all done on this back end.

Now I am much more-- I'm a physicist by degree, but my whole career has basically been on lens design and lens test. So this is really more my sweet spot. This lens, we can characterize it a few different ways. So there's seven different lenses. So that tells you there's an awful lot that goes into this, because we're looking at a very specific band. And so that drives how many lenses we need and what materials that need to be made out of.

And we have to match our detector. Because if we image light and then use a detector that isn't very sensitive to that particular wavelength of light, not going to get a very good image. But there is one thing I wanted to stress about TESS. So your phone takes really nice, clear pictures, and you can take pictures with your friends and they're nice and clear. TESS is not that kind of camera.

So if you think about what TESS is trying to do, it's trying to look at a very wide field of view, a huge area. And does anyone know what typically happens when you have a camera and you're trying to look at a very wide field of view with a camera? What do you notice about the edges of the picture? Has anyone ever seen a very wide field of the image? Trying to think of a good example. An old school camera, an old school photo.

The edges of the image are not as good as the center. So if you are trying to optimize your camera to look at a very specific spot, you can do really well in one place, but the further you expand your field of view basically, it's hard to keep the entire field of view in focus. And so TESS is not really concerned about taking really pretty, sharp images. All it needs to do is-- basically, we call it a light bucket. It's trying to collect the light from the stars in a small enough spot that we can notice that little change in the light curve.

So it's kind of a totally different type of camera. It's not a pretty pictures camera. It's a light collection camera. And the other key thing to think about when you're designing a camera, so what are you trying to do with it? But also, where are you trying to do that? So TESS is going to operate. We design it on the ground at a normal temperature for you and me. But there's a lot of adjustments that have to go into the design to make sure that when it's up in space and really cold, that it will operate as intended. So there's a lot that goes into the camera design. It's not just what you're going to do, but where you're trying to do it.

And so this is where TESS fits into the exoplanet puzzle. We talked a little bit about this before. So I wanted to put these pictures in, because they look so different, right? So this is what Kepler looked like. It was looking at a very specific section of sky. So it was doing something different. It was looking at a very narrow field of view, and very specific planets. TESS, you've seen we've got four cameras. And our goal is to just go up there and find planets, but not really characterize them.

And then James Webb looks totally different than we do. It's got multiple instruments on the same spacecraft, and it's going up there, and it can actually characterize the atmospheres of the planet. So we get one step closer to finding out if there really is another Earth-like planet up in space.

All right, so just to kind of close out. So we've talked about a bunch of different cameras. And one thing I want to stress, they're used in so many different fields. Even if you don't want to be a camera designer, just understanding how they work and how different things affect them can be useful to you in so many different fields now. Because even if you're into something that's not really super technical, you might end up using cameras.

And so I think no matter what you choose to do, it's nice to have that ability and to really understand how they function. But if you do really get into it, there's an awful lot of different areas that you could really focus on and I think make a huge difference in your field. So what you can do with cameras right now is have some fun. So I hope you guys have a great day, and I hope you have fun building the cameras and figuring out if maybe optical engineering or detector or signal processing is your passion. So good luck with the rest of the day.

[APPLAUSE]