PROFESSOR: And let's get on to once you actually collected light with a telescope what do you do with it? You need some sort of detector. And that means the light has to be converted in a signal that you can measure.

Now, historically people first looking with the naked eye. What happens there is photochemical reaction that converts that into a nerve impulses, which your brain registers. So essentially no matter what you do actually you want to convert energy of light into moving electron current somewhere.

Photography was the workhorse of astronomy for almost a century. Then we went to photoelectric devices. Now we do all manner of solid state devices. I'll talk about some of those. And today essentially all astronomical detectors are applications of solid state physics. And all of them basically operate on the same principle. You have to capture a photon, turn its kinetic energy into an electron that can be then accelerated by some voltage and measured. And so you need a lot of photons to get measurable currents.

They're characterized by sensitivity of different wavelengths. They each have noise, and so on. And the important quantity people talk about is the quantum efficiency, which is essentially what fraction of all photons hitting your detector are producing measured signals. Could be one electron or a whole bunch. It doesn't matter.

The old fashioned way of going about it, which I'll describe because it actually kind of describes the principle of it, was through photomultiplier tubes. You're probably familiar with the photoelectric effect. The simple version of it is there's a cathode, a negative charge anode, cathode is heated, there is a little cloud of electrons, photons come in, knock out the electrons, which can then be accelerated by the voltage. This is how the old fashioned diodes work.

Now, do this in multiple stages. Have a little cathode. Photons come in, knock out the electrons. They're accelerated towards the first anode, gain some energy because of acceleration due to voltage, knock out a whole bunch of electrons, and then again, and again, and again. And you do it several times, and you turn one incoming photon into like a million electrons at the end. You're still having same detected quantum efficiency, but at least you can measure this current. And so this is how photo multipliers work.

Very similar operation for the solid state devices, except it doesn't happen in vacuum with caught electrons and so on, but all happens inside the crystals. And different materials can be used for different wavelength regimes. And this is different types of detectors. And so silicon typically goes from about 1 micron through 0.3 or so, and in each case it becomes opaque.

Almost all of the modern detectors, invisible, ultraviolet, infrared, and now actually X-rays as well, are so-called Charged Coupled Devices, or CCDs, or charged metal oxide semiconductor arrays. Those are the detectors that are in your webcam. Two people who invented CCDs got the Nobel Prize for it couple years ago, and well deserved too. So those are fabricated on wafers in the same machinery that makes integrated circuits. And usually there is some grid of pixels that are connecting wires behind it, and then there is some way of plucking the charge and reading it out.

You first of all want to cover the detector with some coating so it doesn't reflect too much. Otherwise you get a mirror but don't get any light. Then you have to generate charges, and this is done internally inside the crystal. And I'll show you in a moment how that's done. Then somehow you have to collect the charge. Move it out in a way that's controlled, as where it is in the focal plane, and then those are the pixels. You have to move it without really losing too much of it. That's impossible. And it's still a tiny amount of charge, so you have to amplify it. So there has to be little amplifier in that device.

But systematically this is how it works. In any metal or semiconductor there is a little sea of electrons that has sufficient energy, and so it's called conduction band of energy, and those are the ones that controls current. Then there is a gap in energy called a band gap, and it's the valence band that corresponds to energies for chemical reactions. So what you want is the way to knock out the electron from valence band, move it up into conductivity band so it can be moved and measured. And so that band gap is of the order of electron volts typically, through visible light. And there are many, many details about this, but that's the basic idea.

So you could in principal collect charges, but how do you actually turn it into an image? Well, the way this works is instead of having one electrode in each pixel to read it out you have three. And you turn one of them, the middle one, positive, and the two around it negative. And so that creates a potential well that electrons will only accumulate in the middle where there is a positive charge, positive voltage. And then when you're ready to read it out then you just shift the pattern by one and shift by another. And so you essentially clock out that whole pattern of potential wells and pick it out at the end and amplify it. That's essentially how all CCDs work.

And that's a schematic diagram. So you have this blob of electrons that have been accumulated through photoelectric effect, and then just moves, moves, moves, they spread out.

The infrared arrays operate in a fairly similar principle but not exactly the same. There every pixel actually has its own little readout electrode. And those are produced in a slightly different way, but by and large most of the operational issues are very similar. And different combinations of metals are used in order to tune this band gap, which then tells you what wavelengths you can observe.

The last modern type of optical detectors is these CMOS imagers, and those are also made using same VLSI technology, like integrated circuits, so it can be made fairly large, and they have now replaced CCDs in most of the digital cameras. For professional, scientific uses, we still use CCDs. But webcams and stuff like that is pretty much all it is. So each one of these, pixels again, has its own little amplifier, and can be read out separately. And thanks to Moore's law we can make arbitrary complex arrays of these. This is what's used today.

The future is ideally you'd like to be able to measure energy of each individual photon comes in, as well as where it comes in your image, and at what time. Now, currently we cannot do this, but there are new generations of devices which are just beginning which use super conductivity. And they're essentially extremely precise thermometers. Some of them operate on the principle of lifting the temperature of the substrate just above the critical so it's no longer conducting. Others break Cooper pairs, but they are the most sensitive devices we have. And they provide some manager resolution for each incoming photon. So that's the ideal detector. Right now they only exist in tiny, little arrays, and they have to be kept cold in liquid helium, but that's where things are going.

Another type of detector, which is heavily use in infrared, and in micro background measurements, is so-called bolometers, which are operating a thermoelectric effect. They are thermometers that are highly sensitive to temperature. And again, you absorb a photon that changes the conductivity of this detector, and you can measure this very precisely.

Now an interesting trick that's been developed here by Andrew Lange and Jamie Bock and collaborators are so-called spiderweb bolometers, which put this crystal that actually does the business in the middle of a mesh like antenna. It looks like a spider web. So that antenna can collect photons, as you normally would, and still can convey that thermal change to the tiny crystal in the middle.

Caltech and JPL are actually among the leaders in the game of producing more sensitive detectors. And this is why it's people like Jamie Bock here who measure these amazing things in microwave background.