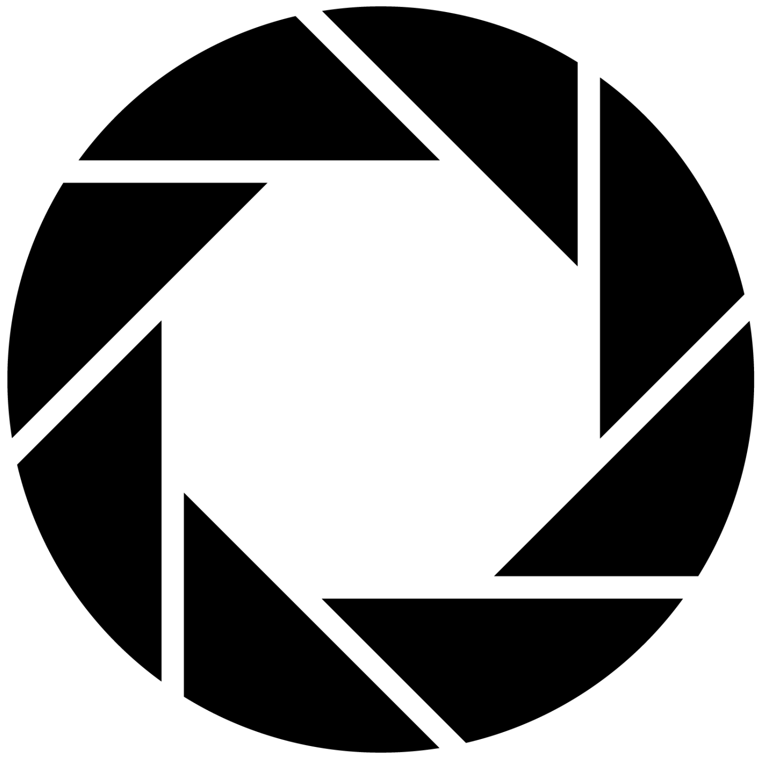
Open Your Shutters

How Digital Cameras Capture Light



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How Can I Develop This: Introduction

Imagine you are walking into a dark room; at first you can't see anything, but as your pupils begin to dilate, you can start to see the details and colors of the room. Now imagine you are holding a film camera in a field of flowers on a sunny day; you focus on a beautiful flower and snap a picture. Once you develop it, it comes out just how you wanted it to so you hang it on your wall. Lastly, imagine you are standing over that same flower, but, this time after snapping the photograph, instead of having to developing it, you can just download it to a computer and print it out. All three of these scenarios are examples of capturing light. Our eyes use an optic nerve in the back of the eye that converts the image it senses into a set of electric signals and transmits it to the brain (Wikipedia, Eye). Film cameras use film; once the image is projected through the lens and on to the film, a chemical reaction occurs recording the light. Digital cameras use electronic sensors in the back of the camera to capture the light. Currently, there are two main types of sensors used for digital photography: the charge-coupled device (CCD) and complementary metal-oxide semiconductor (CMOS) sensors. Both of these methods convert the intensity of the light at each pixel into binary form, so the picture can be displayed and saved as a digital file (Wikipedia, Image Sensor). A photographer can also control the light input through the aperture and shutter speed which can affect how bright the photo is, the depth of field (how much is in focus), and the sharpness of the photo. In this paper, I will show how digital cameras capture light: I will describe the first digital camera and the background of digital cameras, explain how film records light, explore in more depth about how digital cameras capture color, I will introduce the two most common types of digital light sensors, and finally, I will show how photographers can control how the picture comes out through adjusting the aperture and shutter speed.

Snap Out Of It: Background

The first digital camera was invented by Steven Sasson in 1975. It weighed eight pounds and had a CCD sensor with only 1,000 pixels (0.01 megapixels). Since then, there have been many new advancements, modifications, and inventions including new sensors and many new types of cameras (Wikipedia, Image Sensor).

One of the most popular types of cameras is the compact digital camera. Compact digital cameras are intended to be portable and are usually for casual use so they are usually all automatic. To be this small, compact digital cameras tend to have small sensors; compact digital camera lenses are not interchangeable like DSLR or digital single-lens reflex camera lenses. Another type of digital camera is the bridge camera. Bridge cameras physically resemble DSLRs and provide some similar features but, like compacts, they use a fixed lens and a small sensor. The mirrorless interchangeable-lens camera uses larger sensors and offers lens interchangeability. These are simpler and more compact than DSLRs as they do not have the lens reflex system. The modular camera is interchangeable, but the body of the camera has no sensor; the sensor is part of the interchangeable sensor-lens. Digital single-lens reflex cameras or DSLRs use a mirror to direct light from the lens through a separate optical viewfinder which photographers can look through to see exactly what they are taking a picture of. The mirror is moved out of the way to direct the light to the sensor at the time of the exposure, once the shutter opens (Wikipedia, Digital Camera).

Let's Focus On Something Else: Film Cameras

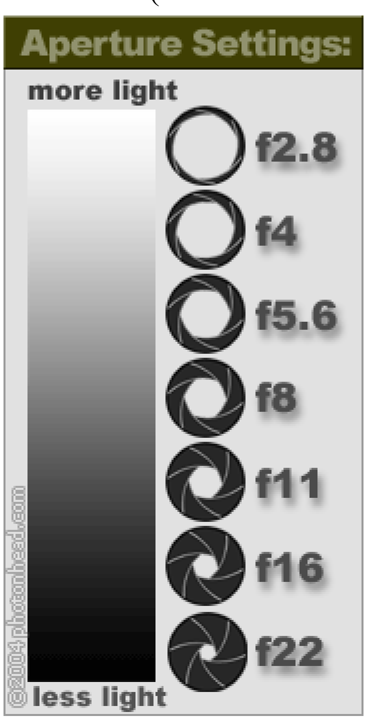
Before digital sensors, most cameras used film to capture light. When the camera exposes the film to light, it creates a chemical record of the image (Harris). Typically, film is manufactured in an encased thin plastic roll of celluloid; both sides are treated with a special chemical blend. One side is coated with chemicals that aid in the development of film negatives, while the other is coated with multiple layers of chemicals that help to form the images that eventually become photographs (Baum). The chemical coatings in the side that allow the creation of images in film mostly consist of silver halide crystals. To make this chemical aspect of film, "silver nitrate and halide crystals are mixed and chemically altered to make them sufficiently small and more sensitive to light photons than they would otherwise be" (Baum). According to Baum, "when they're at the proper stage, they're layered onto the celluloid with additional chemical layers that help to filter and control light photon exposure. All of these layers are attached with thin layers of gelatin." For a picture to be taken, photographers must wind up the film inside of the camera. When they wind up the camera, it stretches the film across the inside of the camera directly behind the shutter or mirror which is directly behind the lens. When the shutter button on the camera is pressed, the shutter opens and closes allowing light photons to be reflected off of the objects in front of the lens and absorbed by the silver halide particles on the surface of the film. "The brighter and more well-lit objects create areas of greater exposure, while the darker and poorly lit objects result in less chemical change" (Baum).

It Was All a Blur: The Effects of Aperture and Shutter Speed

In order for an image to be captured on a sensor, the sensor must be exposed to light. The camera has two settings that control light, and they work very similar to the human eye; these two settings are called the aperture and shutter speed. According to my mentor Jaime Caron, "these aspects of the camera are the parts that have been consistent and essential parts of how cameras work since their inception."

The shutter blocks all light from exposing the sensor until a photographer presses the shutter button. After the photographer presses the shutter, it quickly opens and closes, giving the film a brief flash of light. Photographers can control the length of time the shutter remains open by setting the shutter speed. The longer exposures (like one second) give much more light to the sensor than a 1/1000 of a second exposure. Fast shutter speeds can also help capture fast moving objects such as moving cars and people. Long shutter speeds increase the chance of blur, so, in dark light with a long shutter speed, photographers may need to use a tripod (Photonhead.com). Below, is a chart showing the amounts of light different shutter speeds let in.

Once the shutter opens, the light must pass through an opening called an "aperture." Apertures work like pupils. Like the shutter speed, the aperture also regulates the light that hits the sensor. An aperture regulates the light that hits the sensor by expanding and retracting; the larger the opening, the more light it allows to hit the sensor. The chart below represents the amount of light that each aperture size allows (Photonhead.com).



Although a larger aperture lets in more light, it can also restrict what's in focus. Aperture sizes alter how much of the photo is in focus. For example, if a photographer is taking a photo of a flower from above with a large aperture of f2.8, only the top of the flower would be in focus; while if a photographer was at the same angle taking a photo of the same flower with an aperture of f22, most or the whole flower would be in focus; this variable is referred to as the depth of field (photonhead.com).

Exposed: Methods of Capturing Color

Currently digital cameras use three main methods to record the color of a photograph. The first and most common method is "single-shot." Single-shot cameras take pictures by the aperture opening only once. "Single-shot" digital cameras use either a Bayer filter (only one sensor chip), or three separate image sensors, one for red, one for blue, and one for green; and a beam splitter. Some cameras that use the single-shot method are Canon EOS 50D, Nikon D800, Pentax K20D, and many more. The second method is the "multi-shot" technique. According to Wikipedia, "Multi-shot cameras expose the sensor to the image in a sequence of three or more openings of the lens aperture." The most common application of "multi-shot" uses one sensor; three filters are then passed in front of it to obtain the additive color information. Some cameras that use the multi-shot method are the Hasselblad H4D-200MS and the H5D-200MS. The third method is called "scanning." Scanning cameras use either one line of photosensors or three lines for three colors which move or rotate around the focal plane (the scenery or object the camera is focused on). Some cameras that use the scanning method are the Leica S1, Better Light 6000-HS/6000E-HS, and Phase One PowerPhase FX/FX+. Currently, "single-shot" is extremely dominant over all the other methods because of its simplicity. "Single-shot" is much easier especially when there is a moving subject and even most professional, commercial photographers prefer "single-shot" cameras (Wikipedia, Digital Camera).

Digital camera sensors (CCD and CMOS) sensors can't sense color, they can only keep track of the intensity of the light that hits them. Most sensors filter the light that they receive so it is possible to have a full color image. "Once the camera records all three colors, it combines them to create the full spectrum" (Nice, Wilson, and Gurevich). There are a few very different ways that digital cameras can record color, some are very common, and some not so common (Nice, Wilson, and Gurevich).

A beam-splitter or three-CCD camera is used to make the highest quality of cameras (Wikipedia, Three-CCD Camera). Three-CCD cameras use three distinct CCD sensors, one for each primary color. The beam splitter separates the red, blue, and green, using a dichroic prism, and directs it to its according sensor (Wikipedia, Three-CCD Camera). "Each sensor gets an identical look at the image, but because of the filters, each sensor only responds to one of the primary colors" (Nice, Wilson, and Gurevich). Three-CCD cameras usually take higher quality photos than other cameras but they tend to be "bulky and expensive" (Nice, Wilson, and Gurevich).

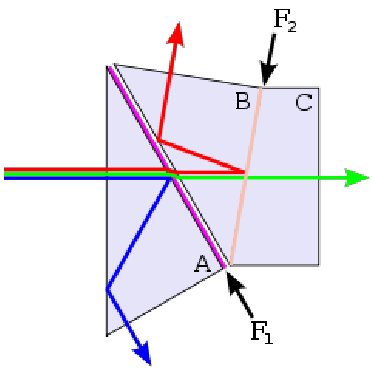


Image courtesy of Wikipedia, Three-CCD Camera

A “beam splitter” or “dichroic prism”

Another more common, economical, practical, and much less expensive way to filter and filter color in digital photos is with a color filter array (Nice, Wilson, and Gurevich). Color filter arrays break up the sensor into a variety of blue, green, and red pixels. Breaking up the sensor into a variety of red, blue and green pixels, it is possible to get enough information in the general vicinity of each sensor to that the camera can then use a technique called interpolation to make an educated guess about the true color at that location (Nice, Wilson, and Gurevich). The most common pattern of color filter array is the Bayer filter pattern. The Bayer filter pattern alternates a row of red and green filters with a row of blue and green filters. “The pixels are not evenly divided -- there are as many green pixels as there are blue and red combined. This is because the human eye is not equally sensitive to all three colors. It's necessary to include more information from the green pixels in order to create an image that the eye will perceive as a “true color” (Nice, Wilson, and Gurevich). “The color filters the light by wavelength range, such that the separate filtered intensities include information about the color of light. For example, the Bayer filter gives information about the intensity of light in red, green, and blue (RGB) wavelength regions” (Wikipedia, Color Filter Array). Only one sensor is needed when using a color filter array camera and, unlike multi shot cameras, all color information can be captured in a single opening of the aperture. This means the camera can be smaller, cheaper, and useful in a wider variety of situations (Nice, Wilson, and Gurevich).

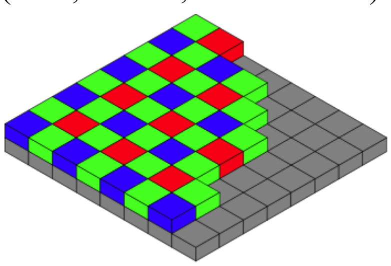


Image courtesy of Wikipedia, Bayer Filter

A Bayer Filter

The Foveon X3 direct image sensor is the last method of capturing digital color information and it is the “most advanced color image sensor ever developed” (foveon.com). According to foveon.com, “It represents a giant leap forward in color photography and is the only image sensor technology that combines the power of digital with the essence of film." The one downfall of color filter arrays is that they only record the information for one color at each pixel. The Foveon X3, like the beam splitter, does not have this problem. The Foveon X3 uses not one but three layers of pixels embedded in silicon to obtain color information. "The layers of pixels are embedded in silicon to take advantage of the fact that red, green, and blue light penetrate silicon to different depths – forming the first and only image sensor that captures full color at every point in the captured image" (foveon.com). Some cameras that have Foveon sensors are the Sigma SD9 and SD10 digital SLRs (foveon.com).

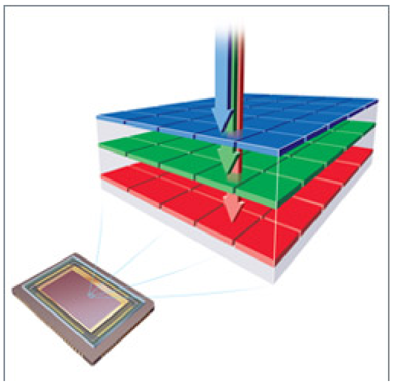


Image courtesy of foveon.com

A Foveon Sensor

Walk Into the Light: CCD and CMOS Sensors

To capture light from an image in digital format, a digital camera uses a special sensor, called a CCD or CMOS sensor (Grundy). Image sensors are used in digital cameras to convert optical images into digital images (Wikipedia, Image Sensor). Both CCD and CMOS image sensors convert light into electrons (Nice, Wilson, and Gurevich). CCD and CMOS sensors are typically the size of a fingernail and the surface of the sensor contains millions of micro-sized sensors that capture a single pixel of the image projected by the lens when the shutter opens and closes. Generally, the more sensors on the surface of the sensor, the better quality picture a digital camera is able to take. When you see references to megapixels in camera specifications, they refer to the number of sensors on the surface of the CCD or CMOS sensor. Digital cameras with higher megapixel ratings generally take higher resolution, or clearer, pictures than models with lower megapixel specifications. "Nikon has spent ten years developing the "snappily titled" JFET LBCAST sensor used in their pro DSLRs" (Atherton and Crabb, 114). "The sensor is made up of individual light-sensitive sites, which read and store the incoming light". According to Gulbins (10), "each individual site builds up a positive charge that allows it to attract the negatively charged photons of the incoming light energy, which it then stores."

There are many differences between CMOS sensors and CCD sensors. CCD sensors create high-quality, low-noise images. CMOS sensors are generally more susceptible to noise. The light sensitivity of a CMOS chip is lower. CMOS sensors traditionally consume little power. CCDs, on the other hand, use a process that consumes lots of power. CCDs consume as much as 100 times more power than an equivalent CMOS sensor. CCD sensors have been mass produced for a longer period of time, so they are more mature. They tend to have higher quality pixels, and more of them (Nice, Wilson, and Gurevich).

A CCD basically "transports the charge across the chip and reads it at one corner of the array. An analog-to-digital converter (ADC) then turns each pixel's value into a digital value by measuring the amount of charge at each photosite and converting that measurement to binary form" (Nice, Wilson, and Gurevich). In a CCD, there is a photoactive region, Silicon dioxide (SiO2), a transmission region, the CCD, and gate electrodes on top. The image that you want to capture is projected onto a capacitor array (the photoactive region) through the lens causing each capacitor to accumulate an electric charge proportional to the light intensity at that location. This process converts the photons into electrons, then into a voltage, and then into binary form. "Once the array has been exposed to the image, a control circuit causes each capacitor to transfer its contents to its neighbor (operating as a shift register). The last capacitor in the array dumps its charge into a charge amplifier which converts the charge into a voltage. By repeating this process, the controlling circuit converts the entire contents of the array in the semiconductor to a sequence of voltages. In a digital device, these voltages are then sampled, digitized, and usually stored in memory. A one-dimensional array, used in line-scan cameras, captures a single slice of the image, while a two-dimensional array, used in video and still cameras, captures a two-dimensional picture corresponding to the scene projected onto the focal plane of the sensor" (Wikipedia, Charge-coupled Device). CCDs are found in "video cameras, light meters and many other devices, as well as a majority of digital cameras" (Atherton and Crabb, 114).

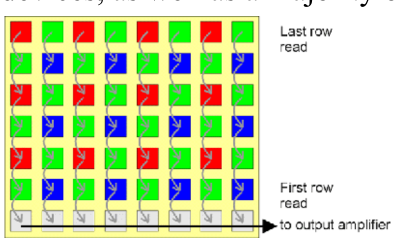


Image courtesy of siliconimaging.com

A CCD Sensor

The CMOS (complementary metal oxide semiconductor) image sensor is a "relatively new" and a much more complex method of capturing the intensity of light and converting it into a format so that computers can read and display it. The predecessor of the CMOS was the MOS (metal oxide semiconductor) sensor. The MOS type of image sensor was released almost 40 years ago (Nakamura). "The biggest advantage of a CMOS sensor is that it is typically less expensive than a CCD sensor. A CMOS camera also has weaker blooming effects if a light source has overloaded the sensitivity of the sensor, causing the sensor to bleed the light source onto other pixels. Since a CMOS video sensor typically captures a row at a time within approximately 1/60th or 1/50th of a second (depending on refresh rate) it may result in a "rolling shutter" effect, where the image is skewed (tilted to the left or right, depending on the direction of camera or subject movement)" (Wikipedia, Active Pixel Sensor). For example, taking a picture of a car moving at high speed, the car will not be distorted but the background will appear to be tilted. Frame-transfer CCD sensors do not have this problem, instead, they capture the entire image at once into a frame store (Wikipedia, Active Pixel Sensor). CMOS chips are known as Active Pixel Sensors (APS) because all the pixels “contain their own processing circuitry,” (Atherton and Crabb, 114). The CMOS chip which “works on the same principle as the CCD, but is manufactured by the process that is used for making most computer memory chips” (Freeman). According to Freeman (13), “It is actually a conventional memory chip with a light sensor in each cell and has the potential to process the information right there, on site.”

A Photo Finish

My original research question was “how do digital cameras capture light?” After all of my research, I found that there are two main types of sensors in digital cameras right now, the charge-coupled device and the complementary metal-oxide semiconductor. Both of these convert light into a digital format so it can be displayed. A photographer can also control the light input through the aperture and shutter speed which can affect how bright the photo is, the depth of field (how much is in focus), and the sharpness of the photo. I predict that in the future, there will be many new methods and techniques that cameras use to filter the intensity of light and color into a digital format. Digital photography is becoming more and more popular but what people don’t realize is that digital photography is more than just snapping a picture with your smart phone.

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