Optical Instruments: Crash Course Physics #41

Crash Course: Physics
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Cameras. They're the reason you can see me right now and they're also the reason why so many precious moments are stashed away safely inside your smartphone. And just like everything else, these visual marvels are possible because of the laws of physics.
To capture an image, a basic camera has a lens that light passes through and a lens opening behind that, which controls how much light enters the camera. Whatever light passes through when a picture is taken strikes the film, or the digital sensor, in the back of the camera to be recorded as a photograph.
But whether or not you're a photographer, every day you're dealing with lenses, images, and keeping objects in focus.
Because even if you've never even picked up a camera or a smartphone in your life, you're probably still using your eyes.

=====(Theme music)=====

Your eyes function a lot like a camera does, adjusting in order to view the world up close and far away.
The iris controls how much light enters your eye opening up while it's dark and contracting in the presence of bright light. The lens in your eye is controlled by muscles that change the focal length in order to focus on objects at varying distances. The incoming rays that enter through the cornea strike the retina at the back of the eye. The retina acts as the sensor that captures the image, sending it to the brain in the form of electrical signals. The fovea is at the very center of the retina about a quarter of a millimeter wide. This small area is the source of the sharp central vision that you use while reading or focusing on a single point.
Let's do a little demonstration to see just how good your eyes are at producing a sharp image.
Cover one of your eyes with one hand, and with the other hold something up with writing on it like a physics textbook or a grocery list.
Now start with the text very close to your eye and start to slowly move it away until it comes into sharp focus. Found the spot? Congratulations, you've located your near-point, the closest distance your eye can focus on an object.
When someone has a near-point that is further than average which is around 25 centimeters they have hyperopia, or commonly known as being far-sighted.
Someone who is far sighted can see distant objects just fine. But when objects are too close their eyes can't make light rays converge at the retina instead the image forms beyond the retina. This can be corrected by eye glasses with converging lenses that bring light rays closer together to form a clear image on the back of the retina.
Now if you have the opposite problem and have a hard time focusing on distant objects then you have myopia, also known as being near-sighted.
In this case the eye causes light rays to converge too quickly, causing the image to form too far in front of the retina. So near-sightedness can be corrected by diverging lenses, spreading out the light rays so a focused image is formed at the proper distance.
But lenses can not only correct problems you have with your vision, they can also produce images of things that would be indecipherable to anyone, no matter how good their eyesight is.
Let's start small and take a look through a magnifying glass. Any simple magnifier consists of a single converging lens, which produces a virtual image that enlarges an object.
And you can use a trusty ray diagram to show how this image forms.
If you had, say, a small leaf that you wanted to inspect, you'd just put the leaf inside the focal point of the magnifier. Since the leaf is inside the focal point, the rays diverge, and the lens forms a virtual image that's much larger than the original object. And ideally, this virtual image forms just past your near point, because if it were closer, you wouldn't be able to focus on it.
Now, you can measure a lens' magnifying power by comparing the angles at which light rays enter your eyes.
Every object takes up some amount of your field of vision. And mathematically, you can express that in terms of how much that object subtends.
An object is said to subtend a certain angle of your vision based on how close you are to it, and how big it is. For example, if you're looking up at the moon, and you cover it with your thumb, then your thumb and the moon are both subtending the same angle to your eye, which we measure in degrees.
So if you look at our tiny leaf, it may subtend only two degrees of your vision when it's at your near point, say, 25 centimeters away. But when you look at the leaf through the lens, the virtual image is larger than the actual object, so it subtends six degrees of your vision. In order to find the magnifying power of the lens, you just divide the angle subtended by the virtual image by the angle subtended by your unaided eye. This equation, which holds true for all magnifiers, tells you that this particular lens has a magnifying power of three.
So that's how a lens can magnify something right in front of you. But what about an object that's very far away? Like, VERY far away?
(4:25) *clasical music*
In the early 17th century, telescopes were developed in Holland that could magnify distant objects by three or four times. Our friend Galileo heard about this, and in 1609, he built his own telescope that magnified objects thirty times.
(4:38) This was a refracting telescope. It consisted of an objective lens on the end closest to the object and an eyepiece at the other end, which magnified the image produced by the objective lens. While Galileo used a concave lens for his eyepiece, the standard refracting telescope uses a convex, converging lens for both the objective lens and the eyepiece.
Heres how it works.
The objective lens takes incoming light rays from a distant source. Since the source is so far away, the incoming rats are considered parallel. The objective lens then converges the light rays to form a real, flipped image inside the telescope. This image is very small, but the eyepiece acts as magnifier, forming a large, virtual image for the observer to view. Note that the real image is positioned just inside the focal point of the eyepiece, maximizing the size of the virtual image. And the resulting virtual image is still flipped, so any objects viewed through the refracting telescope would be upside down.
But that can be corrected by using a concave lens for an eyepiece, like Galileo did.
Now, if you want to calculate the magnifying power of the telescope, just start with the same equation you used for the magnifying lens, but with a negative sign, because the image is flipped. The original subtended angle is the subtended angle of the unaided eye, the angle between the center of the objective lens and the height of the real image. And the newly subtended angle is the amount that the object subtends when viewed through the eyepiece, the angle between your eye and the rays from the eyepiece. Since the angles here are so small, you can just assume that the tangent of an angle is roughly equal to the angle itself. And in a ray diagram, you can see that the tangent of the first angle, theta, is the height of the real image over the focal length of the objective lens. That's the distance at which parallel light rays converge after passing though a converging lens. Likewise, the tangent of the second angle, theta prime, is equal to the height of the real image over the focal length of the eyepiece.
You get maximum magnification when the real image is just barely inside the focal length of the eyepiece. In which case, all of the rays passing into your eye from the eyepiece are almost parallel.
Using your small-angle approximation, you can then replace the angles in the magnification equation with the new expressions in terms of image height and focal lengths. After all of the like terms

cancel out, you're left with a magnification equation in terms of the focal lengths of the objective lens and the eyepiece.
Galileo pioneered the use of refracting telescopes in astronomy. But today, many other types of telescopes are used for space research. Many, like the Hubble Space Telescope, are reflecting telescopes, using mirrors as the objective lens so that they can have huge openings, taking in as much light as possible in order to best capture images of distant objects.
These mirrors are convex, causing rays to converge into a real image, which is then magnified through an eyepiece or projected directly onto a digital sensor.
Now let's switch gears and shrink back down to the small stuff. A simple magnifier isn't enough to study objects on the cellular scale, so we've developed compound microscopes, which like telescopes, use objective lenses and eyepieces to magnify objects. Only this time, the object distance to the objective lens is much smaller.
The object is placed just beyond the focal point of the objective lens, so light rays again form a flipped real image on the other side. And just like with telescopes, the real image is just inside the focal point of the eyepiece, generating a large virtual image for the observer to view.
Now remember, for all of these optical instruments, our original optics equations still hold true!
We have the magnification equation, expressed in terms of subtended angles, but we can still use the equations in terms of distance and height for both objects and images.
Likewise, the thin lens equation is still applicable in most of our basic situations. Remember that? It's the equation that relates the object distance and the image distance the the lens's focal length.
Now, as amazing as our technology has become for capturing images, we can't escape the fundamental wave nature of light.
When we first learned about how light travels as a wave, we saw how light passing through a thin slit spreads beyond the edges of the slit.
This diffraction, which is the reshaping of light by obstacles, happens in lenses too.
Since lenses have edges, the incoming rays will always diffract and produce slightly blurred images, even if the lens is perfectly crafted.
For instance, a single point of light, when captured by a camera, will appear as a central bright spot, known as a diffraction disk, with weakening circular rings of light spreading out from it.
The ability of a camera to produce images of points very close together is called resolution, a term that you've probably heard before.
The higher the resolution, the clearer two points that are close together will appear in an image.
For telescopes and microscopes, the ability to resolve an image becomes more difficult as the magnification gets higher, because the diffraction patters that they create are magnified, too.
So, the magnifying power of optical tools is limited, because light acts like the wave that it is.
end music
Today, we learned about the human eye functions like a camera. We also studied simple magnifiers and how to generate an enlarged virtual image. Then, we analyzed how refracting telescopes and compound microscopes function using the same principles. Finally, we discussed how the wave nature of light affects the resolution of images in cameras and all optical instruments.
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