Figure 1: Practical physical simulations

Grassroots Photography, Modeling and Geometry

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On February 18, 2021 Perseverance landed safely on Mars and minutes later we saw its first photographs from the surface of Mars. That landing, like the safe return of Neil Armstrong, Buzz Aldrin and Michael Collins on July 24, 1969 from our first trip to the surface of the Moon was a triumph of theory, modeling and many years of physical experiments – for example, astronauts rehearse space walks in NASA's Neutral Buoyancy Laboratory (the left side of Figure 1) and more mundane but equally necessary elements of life in the "weightlessness" of space (the right side of the same figure) at the Johnson Space Center in Houston. As you and your students investigate Grassroots Photography, Modeling and Geometry you will bounce back-and-forth among modeling, geometry and taking pictures, between theory and hands-on experience.

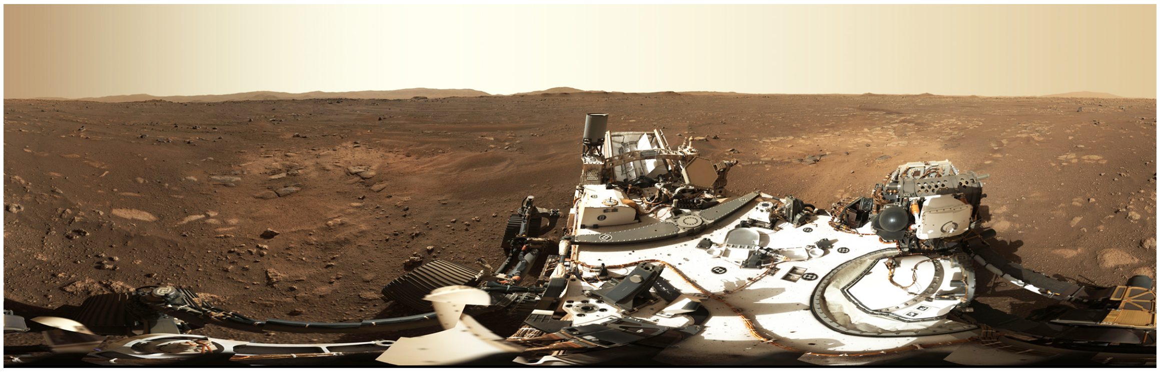


Figure 2: A panorama from Mars

Figure 2 shows one of the first images Perseverance sent back to Earth – a 360 degree panoramic view made using some of the same technology you probably have in your cellphone – see, for example, the "Panorama (up to 63MP)" line in the specs for Apple's $399 iPhone SE shown in Figure 3.

Whatever camera you use, a little modeling and geometry can help you create the photographs you imagine. If you're thinking about buying a new camera, especially if it is part of cell phone purchase, the same modeling and geometry can help you make a good choice. That iPhone SE, for example, has a 12-megapixel camera, 28mm $f/1.8$ camera – what do those numbers mean for the pictures that you want to take? The much more expensive (starting at $1099) iPhone 12 Pro Max has three 12-megapixel cameras: an ultra-wide $f/2.4$, 13mm camera; a wide $f/1.6$, 26mm camera; and a telephoto $f/2.0$, 65mm camera – what do those extra cameras and numbers mean for creating the photographs that your imagination thinks up?

Figure 4 shows the first model we will use to help answer those questions. Instead of the lenses found on real cameras, our first model uses a pinhole. The film or sensor is behind the pinhole. The reason that we don't use pinhole cameras is that they require a lot of light and long exposure times. Nonetheless this simple model is useful for understanding many of the phenomena that are important for photographers. Models like this one and the theory we develop based on these models are important but they are only half – and the least important half – of our investigations. The more important half is practical, physical experience. The real power of our work is the interplay between the two.

Probably the most important quality of a camera and lens combination is its field-of-view. Figure 5 shows two photographs taken with a 35mm camera. The top photograph was taken with an ultra-wide lens with a focal length of 24mm and has a very wide field-of-view. The bottom one was taken with a telephoto lens with a focal length of 90mm and has a much narrower field-of-view. The camera on the iPhone SE has a 35mm equivalent

Camera	12MP Wide camera
	ƒ/1.8 aperture
	Digital zoom up to 5x
	Portrait mode with advanced bokeh and Depth Control
	Portrait Lighting with six effects (Natural, Studio, Contour, Stage, Stage Mono, High-Key Mono)
	Optical image stabilization
	Six-element lens
	LED True Tone flash with Slow Sync
	Panorama (up to 63MP)
	Sapphire crystal lens cover
	Autofocus with Focus Pixels
	Wide color capture for photos and Live Photos
	Next-generation Smart HDR for photos
	Advanced red-eye correction
	Auto image stabilization
	Burst mode
	Photo geotagging
	Image formats captured: HEIF and JPEG

Figure 3: iPhone SE camera features

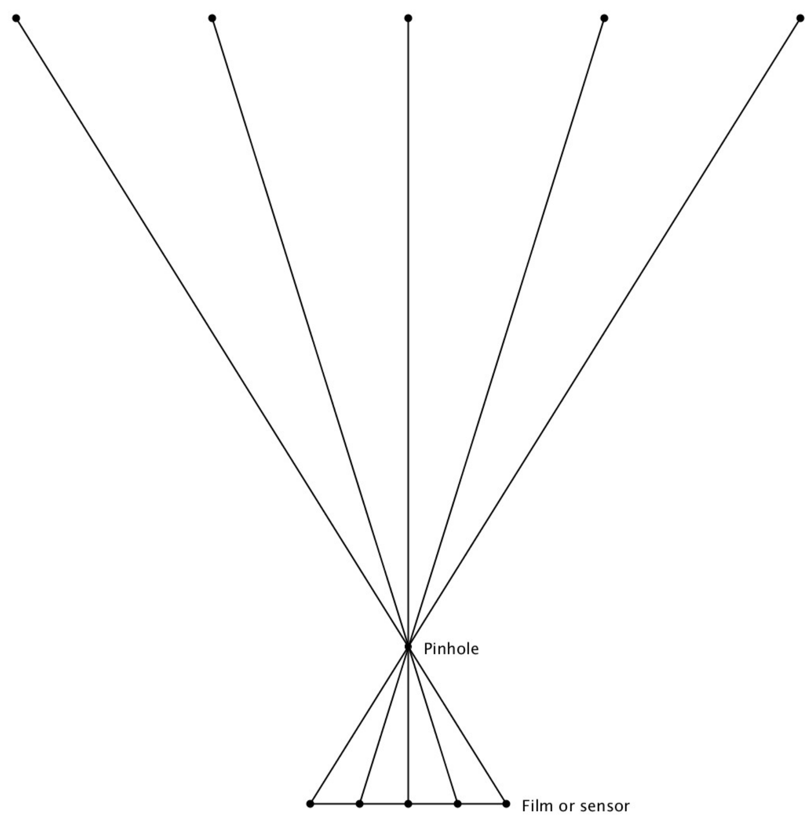


Figure 4: A simple model and experiments in the schoolyard or at home

Figure 5: Field-of-view

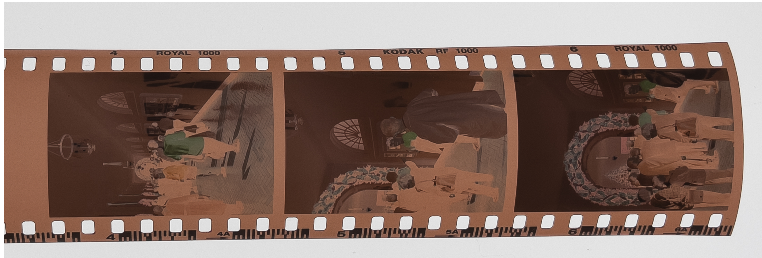


Figure 6: 35mm film

focal length of 28mm – quite wide but not as wide as the ultra-wide 24mm focal length used for the top photo in Figure 5.

Before digital cameras became popular, the most common cameras used film that was 35mm wide. See Figure 6. This film had rows of sprocket holes along the edges to make it easier to move the film. Each image was recorded in a rectangle that was 36mm wide and 24mm high. Each time the photographer pressed the shutter button, one image was recorded and then the film was moved into position for the next image. Because so many people are familiar with the uses of different lenses on 35mm cameras, lenses for other cameras are often described as 35mm equivalents. For example, the iPhone SE's 28mm lens does not have a focal length of 28mm but it does have the same uses as a lens for 35mm cameras that has a focal length of 28mm. The many users of 35mm cameras know immediately that this is a wide angle lens with a wide but not ultra-wide field of view and they have a good understanding of its photographic properties. Even now when many people no longer have had experience with 35mm cameras we still use the language of 35mm cameras – just like we still use the picture (icon) of a physical disk to save files, even though physical disks are a relic of the past.

A lens with a focal length of 50mm is designed to focus images on a sensor that is 50mm behind the lens.[1] We can use the pinhole camera model of Figure 4 to understand fields-of-view. Figure 7 shows how we can determine the horizontal field-of-view of a 50mm lens (on the left) and a 35mm lens (on the right). Your students can determine horizontal, vertical and diagonal fields-of-view of various camera and lens combinations using figures like this and a protractor to measure angles or by using the arctangent function. They can also determine fields-of-views of camera and lens combinations experimentally by making photographs like the ones shown in Figure 8 and measuring the distance from the lens to the yardstick.

[1] A lens is not a single point. Each lens has an optical center and the sensor is 50mm behind the optical center of a 50mm lens. The focal length of the lens is the distance from the optical center of the lens to the sensor.

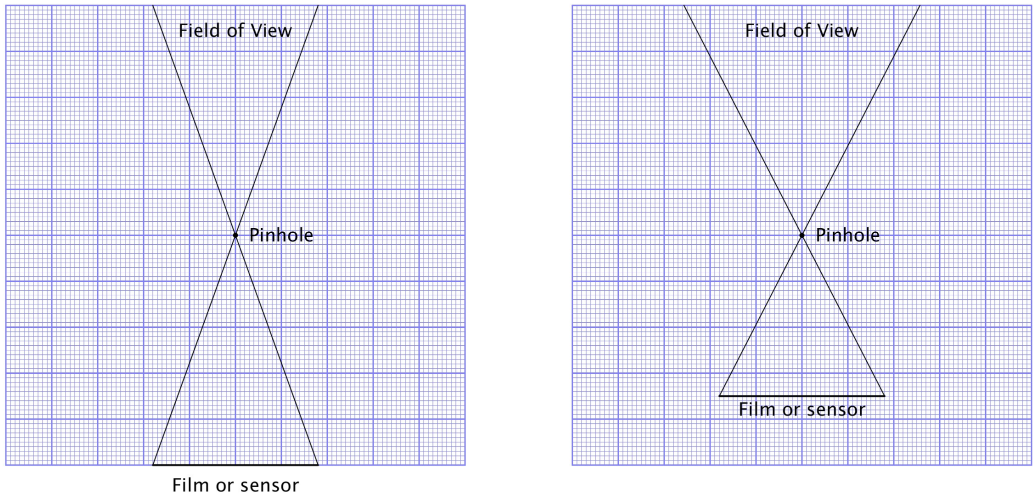


Figure 7: The field of view of a 50mm lens and a 35mm lens on a 35mm camera

Figure 8: Finding the field-of-view of a camera/lens combination

Notice we have been discussing the field-of-view of a camera and lens combination. The field-of-view depends on the focal length of the lens and the size of the camera's sensor. Many modern digital cameras, for example, are designed mechanically to use lenses that were made for 35mm cameras (that is, they use the same lens mount) but they use smaller sensors. Because the sensors are smaller, the field-of-view of a 35mm lens on one of these cameras will be smaller than it would be if the lens were mounted on a 35mm camera with the 36mm by 24mm sensor. Conversely, if a camera with a larger sensor used the same lens and the same mount, it would have a larger field-of-view.

The cameras on cell-phones are very small but their geometry is the same. Everything is scaled down. For example, a lens with a focal length of 3.5 mm on a camera whose sensor is 3.6 by 2.4 mm has exactly the same field of view as a lens with a focal length of 35 mm on a 35mm camera with the standard 36mm by 24mm sensor. This is one of the most important ideas in geometry – similarity. Students typically apply this idea, for example, to find the height of a tree based on the length of its shadow. Now they apply the same principles to create the photographs they imagine.

Cell phones are really thin!! The engineering teams that design cell phone cameras face many constraints – customers want batteries that last a long time but bigger batteries weigh more and require more space; the individual pixels that make up camera sensors cannot be too close together but customers want more of them. Working within all these constraints, these engineering teams can give us the ultra-wide cell phone cameras we want by using sensors that are proportionally the same but much smaller than those used in 35mm cameras.

Many cameras have more than one lens of different focal lengths and many have zoom lenses with variable focal lengths. There are two kinds of zooms – optical zooms and digital zooms. Optical zooms are lenses that can change their focal length but digital zooms fake it by cropping the image. For example, a digital zoom that enlarges a photograph by a factor of 2, called a 2X zoom, crops the picture by a factor of 1/2, using only half the original width and half the original height. It uses 1/4 the area and 1/4 the megapixels of the original image – that 12 megapixel sensor you paid extra dollars for has now become a 3 megapixel sensor!! That's fine for many uses but not so great if you want to enlarge the picture and hang it on your wall.

Figure 9 shows my favorite zoom lens. I used it for Figure 10. The top photograph shows some bamboo trees I pass on a walk I often take. For the bottom photograph I "zoomed in" on those bamboo trees by crossing the street.

The most important decisions you make when you take a photograph are its composition (what you include) and where you stand when you snap the photograph. Often when you take a photograph time is also crucial. For example, you can see from the shadows in Figure 11 that it was taken early in the day or late in the day when the Sun was low in the sky. Figure 12 had to be taken in the winter and Figure 13 in the fall. You will find yourself taking many pictures of the very same scene in different seasons and at different times of the day – and in different weather conditions.

Figure 9: My favorite zoom lens, size 11 medium

Working inside you should try different lighting. For example, portraits taken with light coming from directly behind the camera lack the shadows of portraits taken with light coming from other directions. Shadows create a feeling of three-dimensionality. This is the reason why photographs made with the Sun low in the sky look so different from those taken with the Sun directly overhead. Shadows, of course, are explained by geometry.

Figure 14 shows two portraits of one of my favorite subjects taken with my cell phone. The main subject is about the same size in each and in the center of the photograph but the two portraits are dramatically different. The difference is where I stood when I snapped the photographs. The photograph on the left was taken from several feet away and the one on the right was taken from much closer, so close that I had to use a super wide angle lens to fit the subject in. Notice that the subject is very distorted on the right – his nose is much larger on the right than on the left but his feet are about the same size in the two photographs. The photograph on the right shows much more of his surroundings than the one on the left. Why? Draw some sketches showing why.

This is a great time to take out your camera and explore it. Cell phone cameras are remarkably great and many of us and many of our students carry them everywhere. You can't take pictures with a camera that isn't with you. Although you can learn a lot about your camera using modeling and geometry and by reading its manual and its specs, you won't really know what it can do until you start taking pictures. Explore it now.

Figure 10: Zooming in on a feature of interest

Figure 11: When?

Figure 12: Winter

Figure 13: Fall

Figure 14: Two portraits

Figure 15: 70 Years – Two Cameras

Digital cameras, computers and other new technologies have changed photography in many ways. BATT (before all this technology), each snap of the shutter used film and cost money and photographers had to make many decisions. Now, "film" is electronic storage, reusable, close to free, and occupies little space. BATT, photographers had to set the aperture, shutter speed and focus for each picture. Now, most digital cameras have a fully automatic mode that does all these things. BATT, photographers decided what elements of their photos were important and made their decisions based on what they wanted a photograph to say. For example, a photographer shooting a scene with many people would focus on the person of most interest. She would also choose the aperture and shutter speed to make sure that person was "well lit." Now, the AI (artificial intelligence) used in many cameras builds on techniques like face detection to decide what is important and make camera settings accordingly. The best photographers need to reclaim some of this decision-making from their cameras.

The Kodak Pony camera shown on the left in Figure 15 was produced 70 years ago and sold at the time for the equivalent of about $300 in today's dollars. It could not make cell phone calls like the $400 iPhone SE[2] (on the right) or do many of the wondrous things that the iPhone SE's camera can do, but there is one feature – an f-stop (aperture) control and the depth-of-field markings that went with it –that is missing from even the most expensive modern cell phone cameras that many photographers really miss.

[2]One of eight cameras with prices ranging from $140 - $400, featured in a recent article, *Best budget camera phone: these are the best cheap camera phones right now.* https://www.digitalcameraworld.com/buying-guides/best-budget-camera-phone. Accessed February 22, 2021.

Compare the two photographs in Figure 16. In both photographs the camera was focused on the fence post in the middle. That fence post marks the point-of-focus and is very sharp in both photographs. Compare the bottom left and top right corners of the two photographs. The top right corner is much further from the camera than the point-of-focus and is blurry or out-of-focus in the top photograph but not in the bottom one. Similarly the bottom left corner is much closer to the camera than the point-of-focus and and is blurry or out-of-focus in the top photograph but not in the bottom one. This phenomenon is much more pronounced when the subjects are closer to the camera. Usually we want all the features in our photographs to be as sharp as possible but sometimes we want only the most important feature to be in sharp focus. For example, you often want the background in a portrait to be out-of-focus.

The creative use of focus and blur is one of a photographer's most important tools and cellphone cameras have changed that game – in many ways depriving photographers of a much-beloved tool. As I started writing this note, I looked on the Web to find out as much as I could about cellphones and blur – the more I read, the more confused I got and the story behind that confusion is an interesting one. Textbook learning usually strives to reduce confusion but real learning in the real world is often beset by confusion. In fact, the most important words we utter are "Now, I finally understand." These words usually follow a period of confusion.

Cellphone cameras are remarkably good – almost too good – at avoiding blur – so good that I had a lot of problems making the blurry pictures I needed for illustrations. After a week of growing confusion I finally understand why and this note records how I finally got to that "Aha!" moment.

We need a new model to understand blur. As we noted earlier, pinhole cameras work only with intense light and long exposures. More useful cameras use a larger circular hole (or aperture) rather than a pinhole and a lens that focuses the light rays coming from an object onto the sensor. Figure 17 shows this combination with the camera focused on the black object. All of the light rays from this object that pass through the lens are bent by the lens so that they converge and hit the sensor at the same point. The light rays that come from the red object converge at a point behind the sensor. They hit the sensor in a circular disk, called the circle of confusion. This makes the red object blurry or out-of-focus. How blurry the object appears depends on the radius of this disk. To focus on the red object the lens would have to move forward but this would throw the black object out-of-focus. The two key ideas are:

- The amount of light that reaches the sensor from an object is proportional to the square of the lens' diameter. Why?
- The blurriness of out-of-focus objects is proportional to the lens' diameter. We perceive blurriness by how far apart two objects at the same distance from the camera need to be to appear separated on the sensor – that is, their circles of confusion do not overlap.

Figure 16: Blur and depth-of-field

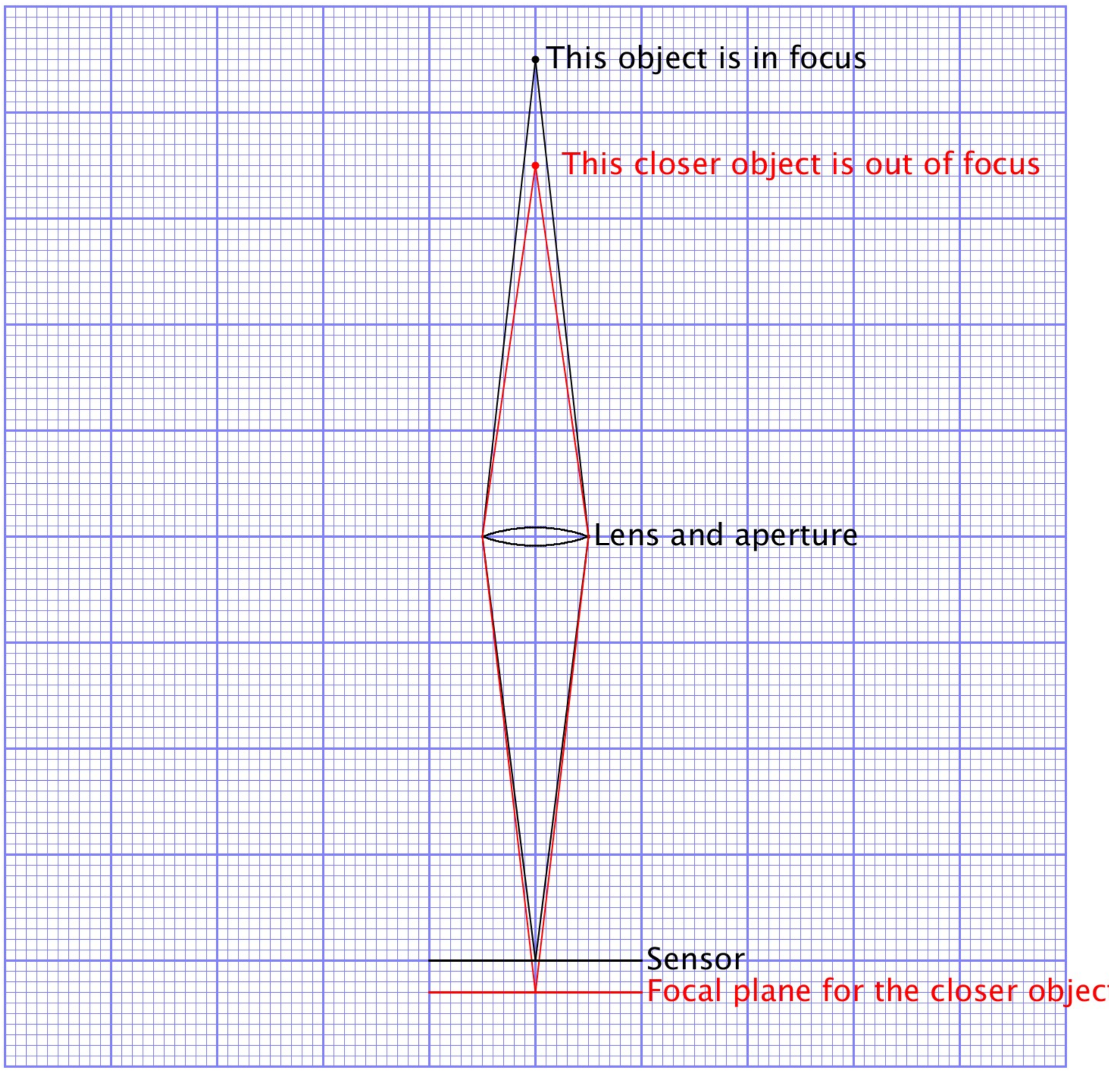


Figure 17: A better model - with a simple lens

We can summarize this by saying that lenses with larger apertures are "faster" but have less "depth-of-field." We use the adjective "faster" because we can use shorter exposures. This is particularly useful if the camera is not on a tripod or the subject is moving. Larger apertures also allow us to work in dimmer environments. Objects that are exactly in focus have to be at exactly the right distance from the camera but objects that are close to that distance will be in acceptable focus. The adjective "acceptable" is important and foreshadows the epsilon-delta definition of limits in calculus, the development of algorithms for approximating numerical quantities and important questions about, for example, acceptable levels of contamination in drinking water or a swimming pool. A photograph that is intended to be viewed on a small mobile device can be shot with a larger aperture than one that will be enlarged for a large screen.

The 35mm equivalent focal length of a camera/lens combination tells us what we need to know about its field-of-view. The f-stop of a lens tells us what we need to know about its "speed" and the f-stop of a lens together with its 35mm equivalent focal length tell us what we need to know about its depth-of-field. Once again, the key geometric idea is similarity. The f-stop of a lens is the quotient of its focal length (actual focal length, not 35mm equivalent focal length) divided by the diameter of its aperture. A lens with an aperture of 25mm and a focal length of 50mm would have a f-stop of 2.0, written $f/2.0$. The f-stop is written that way to emphasize that the diameter is the divisor – bigger apertures correspond to smaller f-stops.

To see how the f-stop of a lens determines its speed we begin with a simple experiment. Take a flashlight (your cell phone may have a flashlight app) and shine it on a nearby wall. With your flashlight move back-and-forth away from and toward the wall. When you and your flashlight are close to the wall the light will be much brighter than when you are further away because as you get further away the light from the flashlight is spread out over a larger area. When you are twice as far away the light is spread out over an area that is four times as large. When you are three times as far away the light is spread out over an area that is nine times as large. The brightness of the light on the wall is inversely proportional to the square of the flashlight's distance from the wall. Similarly the brightness of the image formed by a lens on the sensor is inversely proportional to the square of the focal length – the distance from the lens to the sensor.

The amount of light a lens gathers is proportional to its area – that is, is proportional to the square of the diameter of its aperture. The net result of all this is that the brightness of the image produced by a lens is proportional to the square of its aperture divided by the square of its focal length – that is, inversely proportional to the square of its f-stop. Thus, a lens whose f-stop is $f/2.0$ has four times the "speed" of a lens whose f-stop is $f/4.0$.

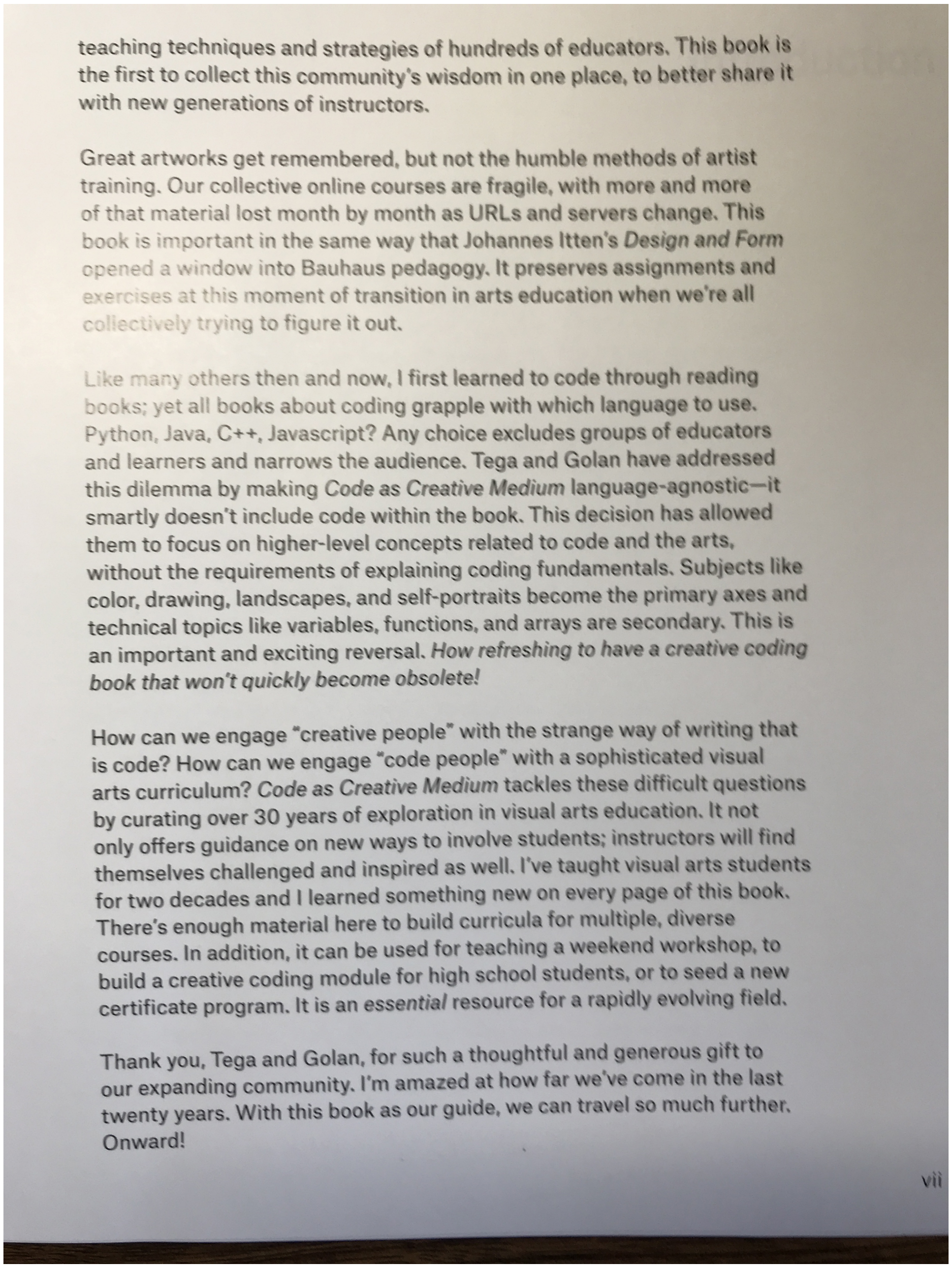
That aperture control in Figure 15 lets the photographer change the aperture and f-stop of the lens and, thus, the brightness of the image it produces. There are other ways a photographer or the automatic exposure control on a camera can change the brightness of a photograph. One way is by changing the length of the exposure. Longer exposures require a much steadier photographer or a tripod.[3] Shorter exposures not only avoid blur caused by an unsteady photographer, but they also avoid the blur caused by moving subjects. Digital cameras, like the ones on cell phones, can also brighten photographs by electronically amplifying the signals produced by the camera's sensor. This comes at the cost of increased "noise." All of this can be controlled by a camera's automatic exposure control but sometimes a photographer wants to make her own decisions – for example, by using a longer exposure time (and smaller aperture) to blur a moving object and create a sense of speed or a shorter exposure (and larger aperture) to stop and study a batter's swing.

In general, telephoto lenses produce more blur and have smaller depth-of-field than normal and wide angle lenses and photographs taken close to a subject produce more blur and have smaller depth-of-field than photographs taken from further away. Photographers often use that aperture control from Figure 15 when they are creating close-up photographs of, for example, flowers to choose higher f-stops (smaller apertures) to get sharper photographs. Conversely, portrait photographers often use lower f-stops (larger apertures) to throw potentially distracting backgrounds out-of-focus. That aperture control gives photographers a lot of creative power. Cellphones' inability to throw backgrounds out-of-focus is so confining that the best cell phone cameras use mathematics, programming and in some cases LIDAR to digitally blur backgrounds for portraits.

We often use our cellphones to take a picture of a page, a map or a blackboard that we want to save. Figure 18 shows one example. This is incredibly useful and cellphones are remarkably good at it. For the best results the phone should be parallel to the thing being copied. Figure 19 shows what can happen if they are not parallel. I focused on the words at the top of the page by touching those words on the screen. The words at the bottom are somewhat out-of-focus. This could be fixed if we had that aperture control. Still cellphone cameras have remarkable depth-of-field and we just have to remember to keep the phone parallel to the thing being copied.

We have mentioned several times that cellphone cameras have remarkable and even unexpected depth-of-field; that the photographs they take are often remarkably sharp; and that it can be hard, for example, for portrait photographers to throw potentially distracting backgrounds out-of-focus. I also mentioned how puzzling I personally found this phenomenon and difficult it was to find out why on the Web. Part of the answer – but only part – is easy to understand. Because wide angle lenses like the ones found on cellphone cameras reduce rather than magnify images they inherently have more depth-of-field. But there is more to the story.

[3] Many modern cameras, including both of the iPhones we've been talking about have a feature called image stabilization that is able to compensate for a photographers's unsteadiness, letting him take sharper photographs with longer exposures.



teaching techniques and strategies of hundreds of educators. This book is the first to collect this community's wisdom in one place, to better share it with new generations of instructors.

Great artworks get remembered, but not the humble methods of artist training. Our collective online courses are fragile, with more and more of that material lost month by month as URLs and servers change. This book is important in the same way that Johannes Itten's *Design and Form* opened a window into Bauhaus pedagogy. It preserves assignments and exercises at this moment of transition in arts education when we're all collectively trying to figure it out.

Like many others then and now, I first learned to code through reading books; yet all books about coding grapple with which language to use. Python, Java, C++, Javascript? Any choice excludes groups of educators and learners and narrows the audience. Tega and Golan have addressed this dilemma by making *Code as Creative Medium* language-agnostic—it smartly doesn't include code within the book. This decision has allowed them to focus on higher-level concepts related to code and the arts, without the requirements of explaining coding fundamentals. Subjects like color, drawing, landscapes, and self-portraits become the primary axes and technical topics like variables, functions, and arrays are secondary. This is an important and exciting reversal. *How refreshing to have a creative coding book that won't quickly become obsolete!*

How can we engage "creative people" with the strange way of writing that is code? How can we engage "code people" with a sophisticated visual arts curriculum? *Code as Creative Medium* tackles these difficult questions by curating over 30 years of exploration in visual arts education. It not only offers guidance on new ways to involve students; instructors will find themselves challenged and inspired as well. I've taught visual arts students for two decades and I learned something new on every page of this book. There's enough material here to build curricula for multiple, diverse courses. In addition, it can be used for teaching a weekend workshop, to build a creative coding module for high school students, or to seed a new certificate program. It is an *essential* resource for a rapidly evolving field.

Thank you, Tega and Golan, for such a thoughtful and generous gift to our expanding community. I'm amazed at how far we've come in the last twenty years. With this book as our guide, we can travel so much further. Onward!

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Figure 18: An image of a page

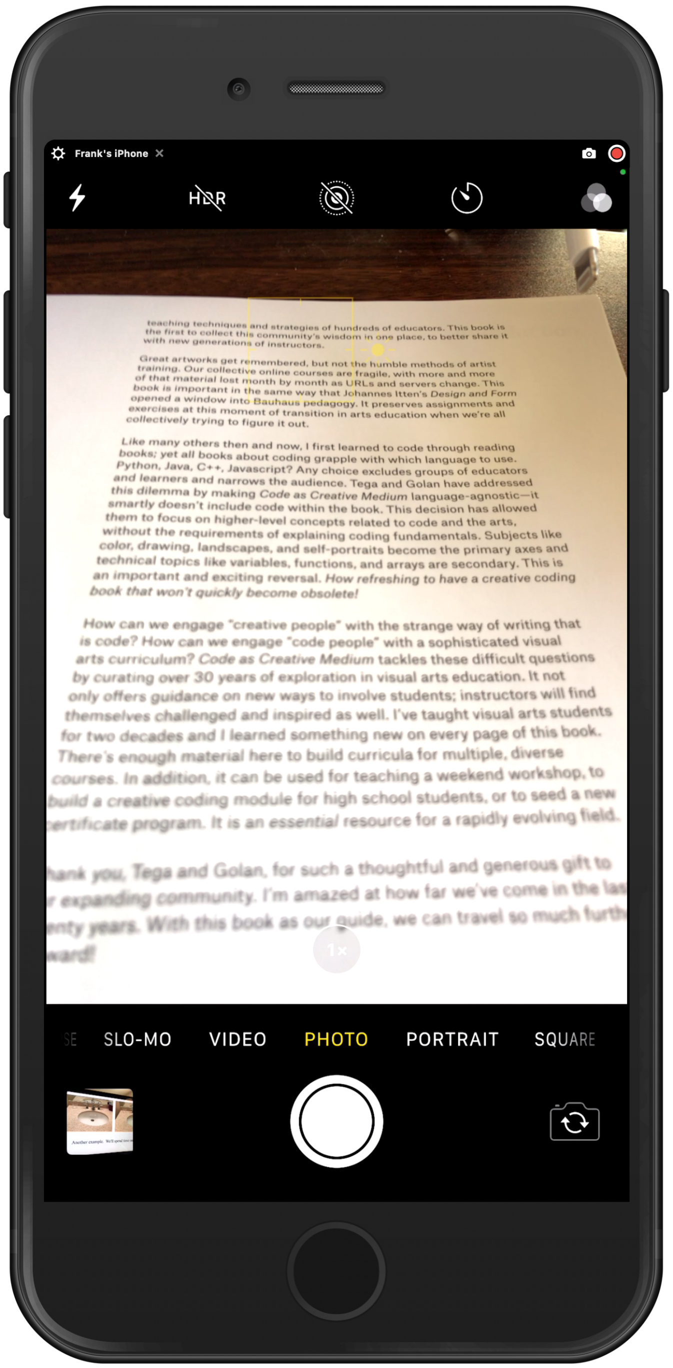

Figure 19: Automatic focus and depth of field for close-ups

The key idea is similarity and the three key figures are shown in Figure 20. The top figure shows a 35mm camera taking a portrait. In the middle figure we substitute a cellphone camera and to see what happens we shrink the entire figure so that the size of the camera now matches that of the cellphone. Notice that the subject of the portrait and its distance from the camera are also shrunk by the same factor. This would give us exactly the same picture as the original 35mm camera, BUT and that is a big BUT the subject has not moved and did not shrink. The situation looks like the bottom figure in Figure 20 – only the camera has shrunk. We get exactly the same picture we would get with the original 35mm camera if the subject was magnified and its distance from the 35mm camera was magnified. See Figure 21.

Analyzing this precisely requires a lot of detailed calculations – beyond what we want to do here. The key is Figure 21. By using a cellphone camera we have effectively moved the subject much further away from the camera. At its new distance the depth-of-field is much bigger. In fact, it is so much bigger that this effect overwhelms the increase in size of the subject. If you were taking a portrait at a typical distance of one meter from a 35mm camera and substituted a typical cellphone whose sensor was 1/5 that of a 35mm camera you would effectively be taking the same portrait at a distance of five meters!! The depth-of-field at that distance is so great that it overwhelms the fact that the subject has also been magnified by a factor of five.

Two good sources for more information are:

- https://www.cambridgeincolour.com
- https://www.photopills.com/calculators/dof

The most important take-away from all of this is two-fold – take lots of pictures and look critically at photographs made by others. Keep the underlying geometry of photography in mind as you think about how you can create photographs like the ones that you see in others' work and the ones that are suggested by your own imagination. In that spirit Figures 22 and 23 are two similar portraits I made with roughly $f/2.0$ lenses, one using a 35mm camera and the other a cellphone camera. Can you tell which is which?

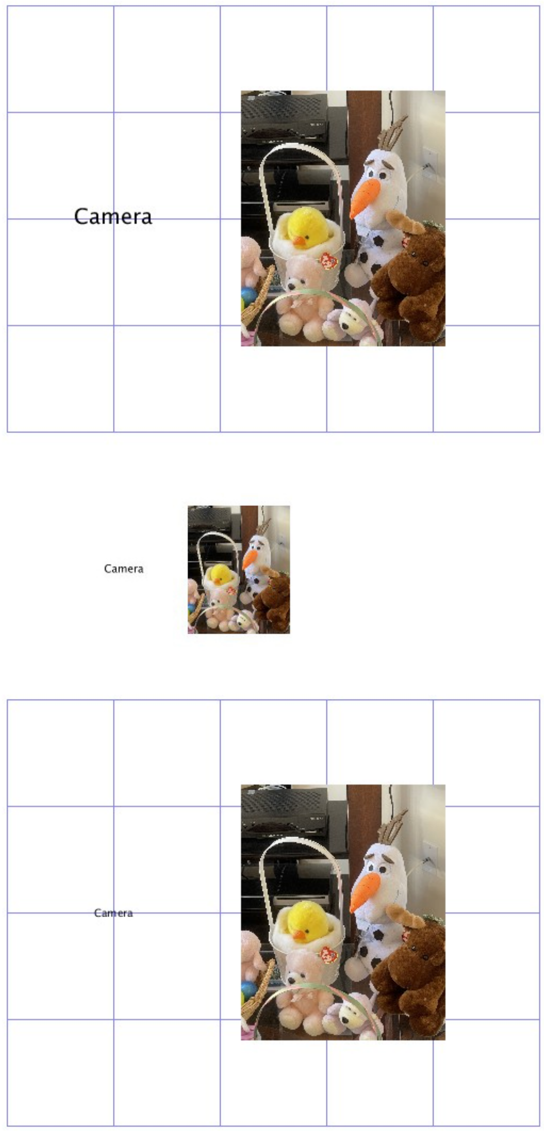

Figure 20: Cellphone vs. 35mm

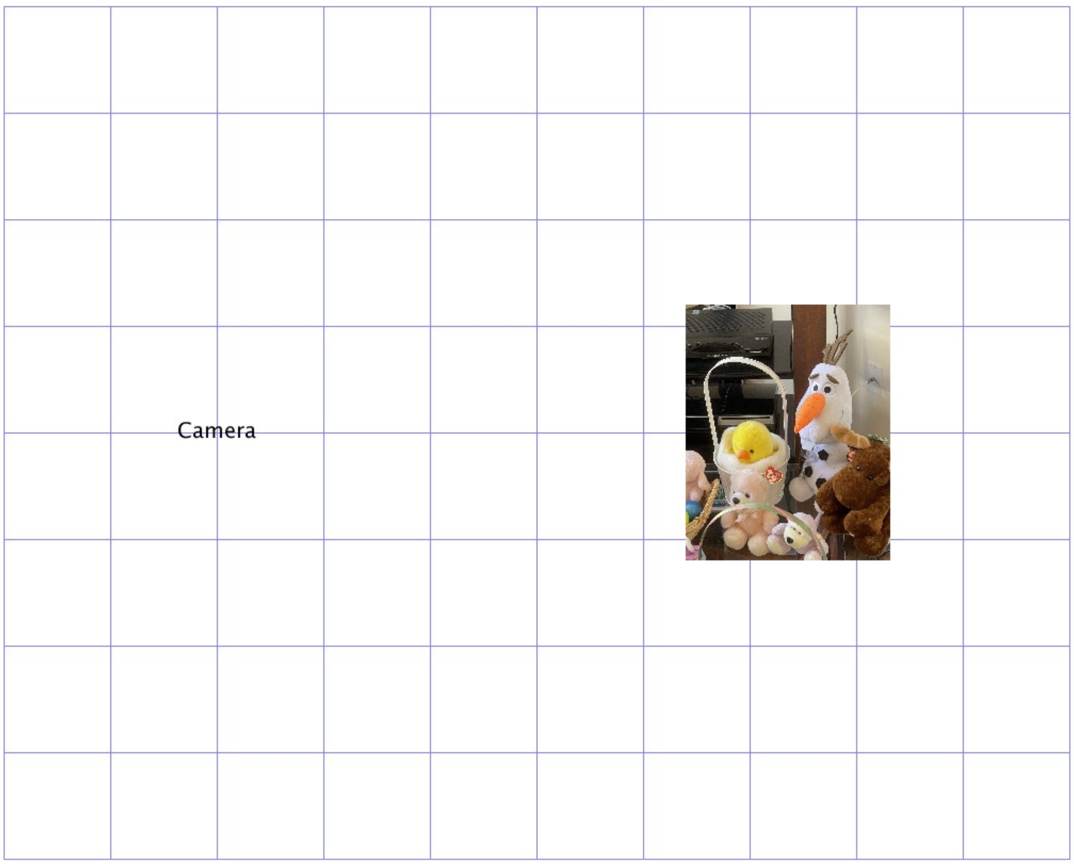

Figure 21: Cellphone vs. 35mm

Figure 22: Portrait

Figure 23: Portrait