The Lens

NK Guy

A Practical Guide for the Creative Photographer

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CHAPTER 1

1

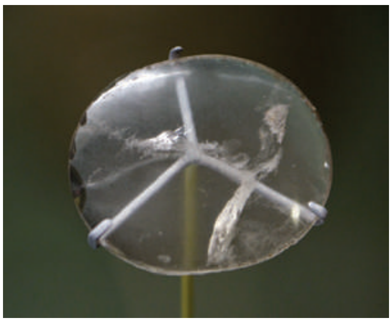
A brief history of optics

1.1 The science of light

At its simplest, photography is about recording waves of light and creating two-dimensional pictures. And fortunately, light behaves in very predictable and reliable ways—at least in a photographic context. Over the centuries the science of optics and the technology of manufacturing have been developed and refined, resulting in the lenses we see today.

This chapter outlines some of the basic historical discoveries that made optical technology possible.

1.2 The path to the lens



▲ The Nimrud lens, made in Assyria (present-day Iraq) around 950 BCE. It's unknown if it had any optical purposes or was purely decorative. The rock crystal is crudely shaped, so I personally doubt it would have been a very useful tool. The British Museum, London, England.

It all starts with light—and the ability of glass to bend it.

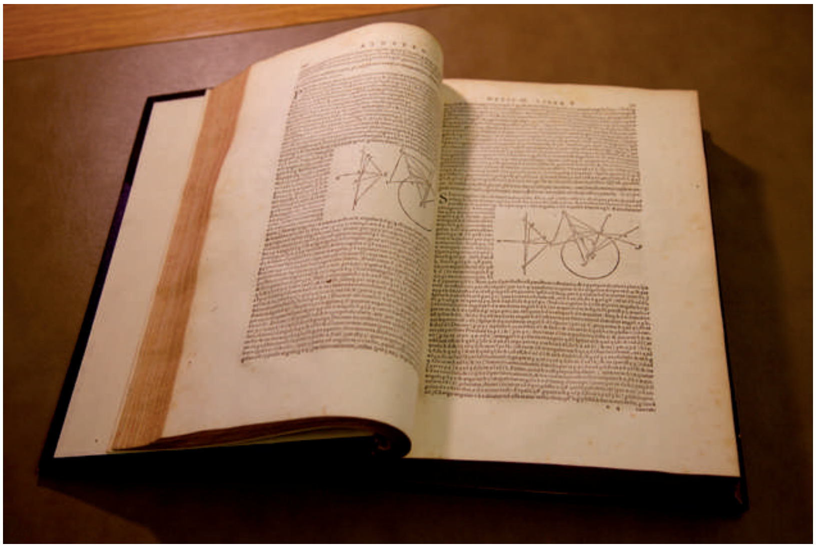
In short, two strands of human knowledge had to come together: a working set of theories to describe how light actually functions and the technical ability to make and shape glass objects.

Lens-making technology dates back thousands of years. Shaped rock crystal lenses were made in ancient Egypt and Mesopotamia, but there is only fleeting and tantalizing evidence that they were used for much more than decorative purposes until roughly the time of the ancient Greeks, when simple magnifying lenses are definitely known to have been made.

Optical theory

As for the science, it actually took quite a while for humans to figure out what light really is and how it works. And some early theories were frankly very strange by modern standards. For example, the Greek philosopher Plato (about 428–348 BCE) and the Roman physician Galen (about 129–216) both maintained that human eyes emit special rays that allow us to see. Oddly this "extramission" theory of light never quite explained convincingly why we can't see in the dark.

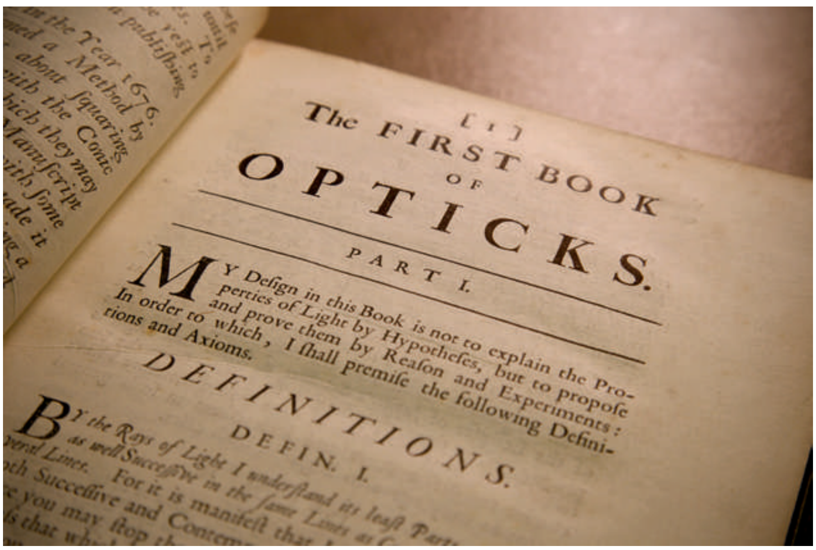
Perhaps the first person to come up with a consistent and modern theory of light was the Arab or Persian polymath Abū ʿAlī al-Ḥasan ibn al-Ḥasan ibn al-Haytham al-Baṣrī (965–1040 or so). He's best known concisely in the West as Alhazen or al-Haytham. al-Haytham correctly realized that light is emitted by light-producing objects, such as the sun or a flame, and travels in straight lines. It then either enters the human eye directly or is reflected off various surfaces first. The eye (or an artificial substitute, such as a camera) is a passive detector of light, not an active emitter of it.



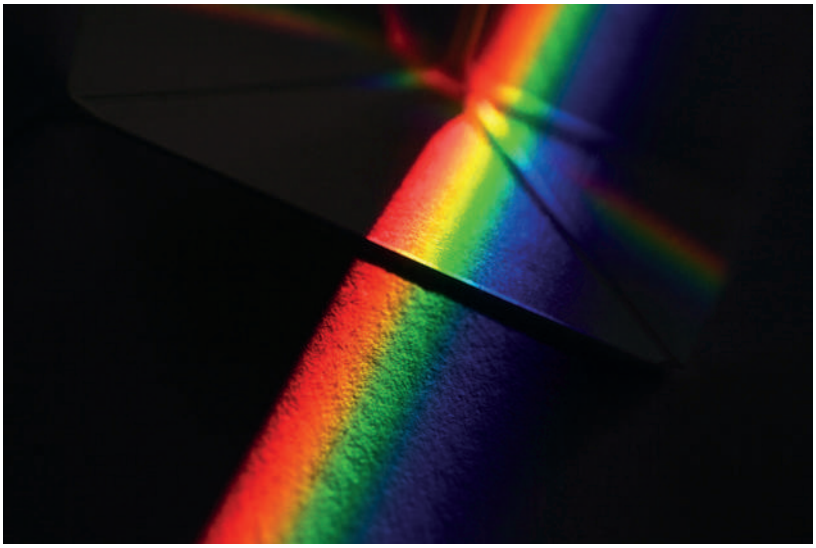
◀ A Latin translation of al-Haytham's *Kitab al-Manazir (Book of Optics),* originally written from about 1011 to 1021, describes diffraction, refraction, spherical aberration, and a host of other optical principles. This 1572 book may be the first printed edition of al-Haytham's work after centuries of handwritten translations and is shown here courtesy the Royal Society, London, England.

While largely forgotten by his contemporaries, al-Haytham's ideas were translated into Latin and eventually took root in Europe. By 1267 English friar Roger Bacon (1214–1294) was writing about optical theory, relying both on his own observations and on the work of others, including al-Haytham.

Some centuries later, German mathematician and astronomer Johannes Kepler (1571–1630) published *Astronomiæ Pars Optica* in 1604, thus establishing the groundwork for modern optics and an accurate model of human vision. Another milestone in the scientific revolution was the publication of *Opticks* in 1704 by English physicist and mathematician Isaac Newton (1642–1727). This work described many optical phenomena, such as diffraction and dispersion.



◀ A first edition of Newton's *Opticks*, in which he discusses the importance of firsthand observation. From the collection of the Royal Society, London, England.



▲ "... in the beginning of the Year 1666 (at which time I applyed my self to the grinding of Optick glasses of other figures than Spherical,) I procured me a Triangular glass-Prisme, to try therewith the celebrated Phænomena of Colours." – Isaac Newton

However, Newton espoused a "corpuscular" theory of light that, while presaging aspects of Albert Einstein's notion of the photon, was eventually demolished by the theory of light as a wave, originated by Dutch physicist Christiaan Huygens (1629–95). Wave-based optics eventually led to the very successful mathematical models of the nineteenth century that made lens design possible.

Today we understand light to be just one form of energy known as electromagnetic (EM) radiation. And it's critically important because, unlike other forms of EM energy, such as radio waves or X-rays, we can see it with our eyes.

Glassmaking

The first optical use of glass was, of course, the development of corrective lenses for human vision. The ancient Greeks are known to have used simple lenses to help perform detailed tasks. And wealthy medieval scholars sometimes used thick hemispherical glass or crystal domes as so-called "reading stones" to magnify text.

► Replica reading stone from the collection of the Zeiss Optical Museum, Oberkochen, Germany.

But it wasn't until the 1400s and 1500s that glassmaking for practical and decorative applications became highly developed. Key inventions included Venetian "cristallo" glass and English lead glass. These very pure materials helped enable the European optical breakthroughs of the 1600s.

Thin glass lenses were devised, resulting in spectacles to assist both reading and distance viewing. Dutch philosopher Baruch de Spinoza (1632–77), for example, earned a good living grinding lenses when he wasn't speculating about the nature of the universe.

▲ A modern-day craftsman transforms a lump of molten glass into a decorative sculpture. Murano, Venice, Italy.

▲ Sixteenth or seventeenth century reading glass and carrying case. Zeiss Optical Museum, Oberkochen, Germany.

With the invention of the telescope and the microscope, optics took people into very different directions of scale. By the early 1600s, Italian scientist Galileo Galilei (1564–1642) had documented the moons of Jupiter and other heavenly bodies. And Dutch microbiologist Antoni van Leeuwenhoek (1632–1723), constructing tiny microscopes by the mid to late 1600s, discovered the tiny "animalcules" (i.e., protozoa or microorganisms) that reside in a drop of pond water.

▲ These strange looking devices are Leeuwenhoek's original handmade microscopes. Of the hundreds he built during his lifetime, only a handful survive today. The lenses are tiny glass spheres located at the center of each handheld tool. The Museum Boerhaave for the History of Science and Medicine, Leiden, Netherlands.

The camera

Oddly enough, the first conceptual "cameras," which can be dated back to China in the fourth century BCE, lacked both lenses and film. They were simply darkened rooms or boxes equipped with tiny pinholes. Such pinhole boxes later became popular with European artists from the 1500s to 1800s as tools to aid drawing in proper perspective.

These cameras exploited the fact that light passing through a pinhole (see section 9.9) or glass lens can be projected onto a flat screen in a darkened box or chamber for viewing. This is the origin of the modern English word, in fact, as *Camera obscura* is Latin for *dark chamber*.

▲ For millennia people have noticed that light cast by small gaps or holes, such as the tiny gap between crossed fingers, will take on the shape of the sun during solar eclipses. This is the same principle that makes pinhole cameras possible. Annular eclipse in Tamerza, Tunisia, 2005.

▲ An experimental camera obscura used in the 1830s by French inventor Louis Daguerre to develop the Daguerreotype, the first workable photographic process. It consisted of a pair of nested wooden boxes that can be moved back and forth like a drawer in order to focus. From the collection of the Musée des Arts et Métiers, Paris, France.

◀ It may look like a model rocketship from a 1940s movie serial, but this amazing device is actually a century older. This is a "Daguerreotyp-Apparat zum Portraitiren," or Daguerreotype Apparatus for Portraiture, made by Voigtländer in Vienna in 1840 or 1841. As a measure of how early it is, remember that Daguerre announced the first workable photographic process to the world in 1839. The lens, designed mathematically by Josef Petzval (see section 1.3), was mounted on the right side, and was covered with a cap which doubled as a shutter. Focusing was done by turning the small knob. Round metal Daguerreotype plates were put into the camera on the left side of the cone. From the Zeiss Optical Museum collection. Oberkochen, Germany.

Photography

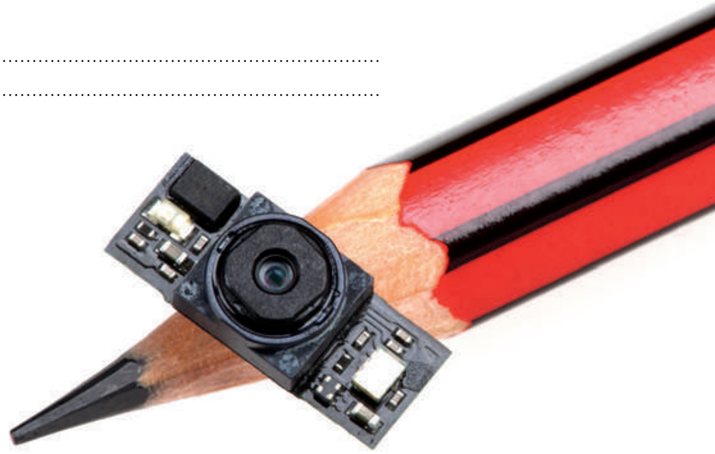
In the 1820s and 1830s, French pioneers Nicéphore Niépce (1765–1833) and Louis Daguerre (1787–1851) invented chemical methods for recording images permanently on metal plates, and photography truly began.

The key elements of traditional photography—dark boxes (cameras), light-sensitive material (plates or film), and light modifiers (lenses)—had come together. For over 150 years these were the fundamental ingredients of image recording.

◀ A mid-twentieth-century film camera: a folding Kinax II made in France in the late 1940s. This is actually my father's first camera.

Considerable research was done in the 1960s and 1970s into electronic imaging—the charge-coupled device (CCD) image sensor chip was devised in 1969, for example. But it wasn't until the 1980s that workable electronic still image-capture devices were introduced. By the late 1990s, digital cameras were rapidly replacing chemical photographic imaging.

▲ The first commercially available digital SLR was the 1991 Kodak DCS (Digital Camera System). It was a stock Nikon F3 camera, with a 1.3 megapixel chip and handgrip bolted on. The camera itself was compact enough, but you also had the huge lunchbox-sized DSU (digital storage unit) containing batteries, voluminous 200 MB hard drive, and preview screen, which had to be tethered to the camera. Only well-heeled news agencies, which valued the ability of the camera to send digital shots down a phone line in record time, could justify the expense and inconvenience of this early proof of concept device.



▶ This photo may look simulated, but it's the real thing. A mere two decades after the Kodak DCS, laptops and mobile phones sport incredibly tiny digital cameras such as this.

Today film is sadly nearing mass-market extinction, but even the latest and most sophisticated digital cameras employ lens technology based on discoveries dating back centuries.

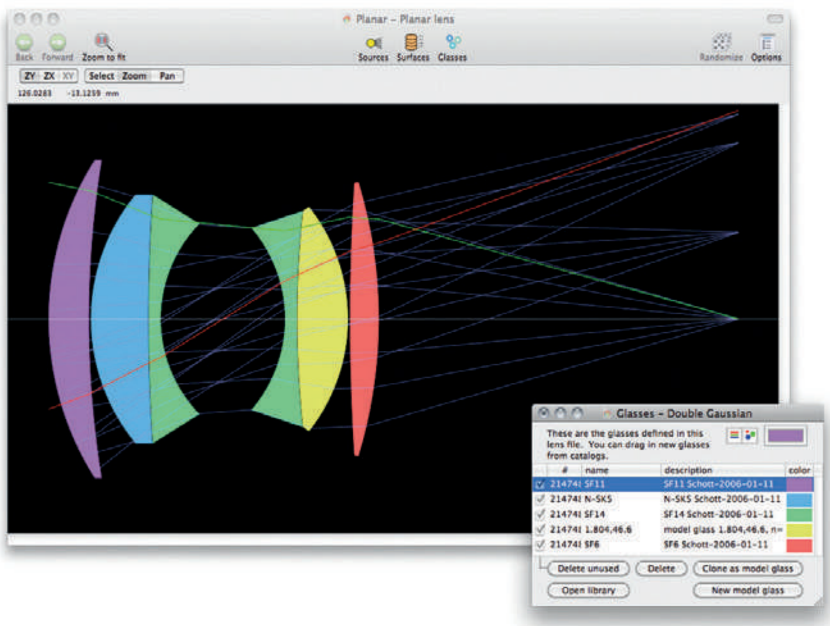
1.3 Geometrical optics

Modern lens design is a very complex and esoteric field and is heavily dependent upon mathematics. The earliest lens makers worked intuitively and pragmatically, testing lens after lens to see what gave the best results. They discovered that certain arrangements of lens types produced sharper images than others, thus creating a family of basic lens designs still in use today.

▶ French opticians Vincent (1770–1841) and Charles (1804–59) Chevalier, father and son, accidentally became the world's first photographic lens makers when their meniscus designs were used by Nicéphore Niépce to take the first photograph in 1826. Charles later teamed up with Daguerre to make the first purpose-designed camera lenses. This is a Chevalier lens from the 1840s "Le Photographe" camera. Musée des Arts et Métiers. Paris, France.

But by the mid-1800s, particularly in Germany, people started to devise practical mathematical equations to predict the way that lenses bend light. These formulas made it possible to calculate the theoretical behavior of various optical designs before they were committed to actual lens grinding and physical testing. Ernst Abbe (1840–1905) at optical manufacturer Carl Zeiss was particularly instrumental in establishing the framework for modern computational optics.

Performing the mathematical calculations was hugely time-consuming in the days before computers, and teams of mathematicians were employed to perform laborious trigonometric and logarithmic calculations on paper. The Petzval lens design of 1840 (used in the Voigtländer camera shown on page 14), for example, took nearly a dozen men several months to calculate. The rise of digital computing dramatically sped up the process and ushered in an age of complex computer models. Today, sophisticated software, advanced forms of glass, and modern automated manufacturing make all kinds of complex lenses possible.



◀ LensForge, a computer modeling program for advanced optics, shows how rays of light will pass through a six-element "double-Gaussian" camera lens. The number crunching behind this simple diagram would have taken a mathematician hours to calculate.

1.4 Waves and particles

Finally, physicists will note that this book discusses only the wavelike aspect of light. It doesn't really deal with the strange dual nature of light, which can also be seen as little particles of energy called photons. This is because from the perspective of a humble photographer, light really only behaves as rays of energy.

CHAPTER 2

2

Bending light

2.1 Putting glass to work

So how does a lens capture light at your bidding?

Each camera lens has innate *optical properties* determined by its designer. Optical engineers put tremendous effort into choosing the shape, number, arrangement, material, and size of each lens component in order to produce a photographic lens with the desired imaging characteristics. This chapter describes some key optical properties.

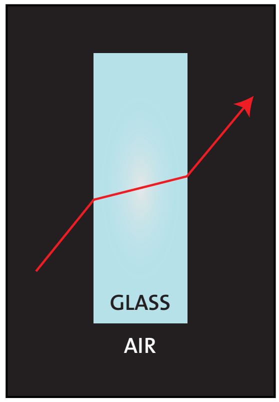
2.2 Refraction

▲ Refraction is demonstrated by this spoon in a glass of water.

Photographic lenses must take light coming in from a scene and then narrow it down precisely to a tiny piece of film or electronics inside the camera. A physical phenomenon known as *refraction* explains how this works.

Refraction simply means that light, which normally travels through space in dead straight lines, can change course when it passes through one transparent material to another.

A classic example of refraction is demonstrated by this spoon in a glass of water. When the spoon is viewed from the side of the glass, it appears to be broken. This isn't because of the curvature of the glass or anything—it's because light traveling through water changes direction slightly upon hitting air. Amazingly, refraction occurs because light, instead of always traveling at the famous speed of light, actually slows down when it's not in a vacuum. Different materials, even transparent substances like glass or water, slow light by differing amounts.



▲ Refraction of light.

Lenses employ the same refractive principle as this glass of water. Pieces of incredibly pure glass (and occasionally plastic or crystal) are carefully cut, shaped, and polished in order to bend light in very specific and accurate ways.

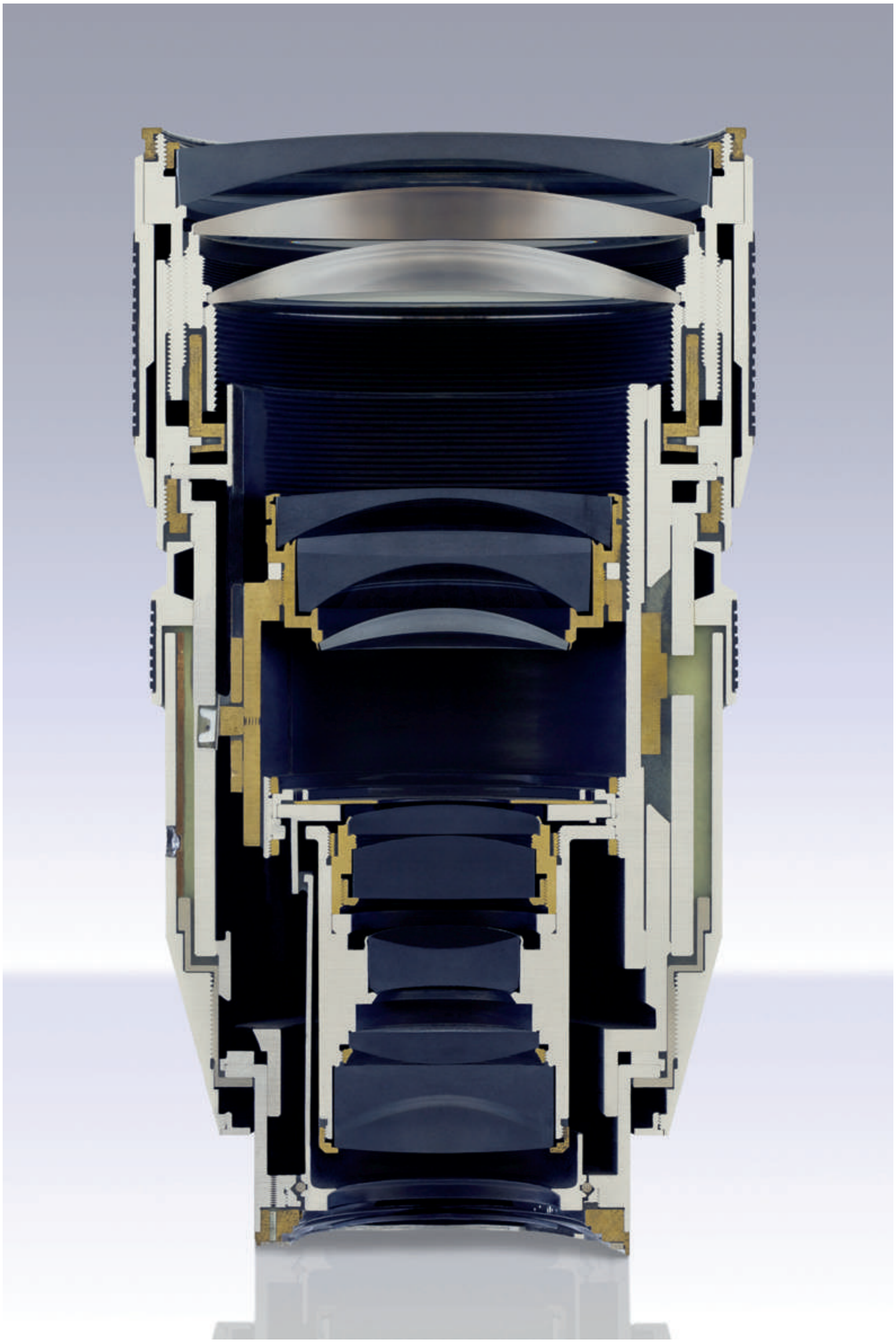
2.3 What is a lens?

The term *lens* is sometimes a bit confusing because the word can refer to a single rounded piece of optical glass or it can refer to an entire barrel-shaped device that fits onto the end of a camera and contains numerous glass discs lined up in a row.

From a lens designer's point of view, however, there's no confusion. A single lens, such as a magnifying glass or one lens from a pair of spectacles, is known as a *simple lens*. Conversely, a camera lens or telescope, involving many separate bits of glass, is a *compound lens* (not to be confused with the multifaceted compound lens of an insect eye). Each single glass piece of a compound lens is known as a *lens element*.

▲ A magnifying glass is nothing more than a simple lens, often with a handle, and represents the starting point in optical technology.

► This is an actual Zeiss Vario-Sonnar 40–120mm *f*/2.8 zoom that has been cut in half. While I can hear cries of anguish from collectors, as it's a pretty rare lens for the Contarex camera, it does mean we get to see the remarkably complex interior. And this is a 1971 lens, so it doesn't even have the computer chips, autofocus motors, or image stabilizers found in today's lenses. From the Zeiss Optical Museum, Oberkochen, Germany.



2.4 Lens elements

Virtually all camera lenses sold today contain multiple lens elements. This is because they must modify incoming light in very complex and subtle ways; something that a single lens element alone can't do.

Each element will have a specific shape or size, depending on what task the lens designer wants performed. Elements can be arranged together, or even glued using transparent optical cement, to form a lens *group*.

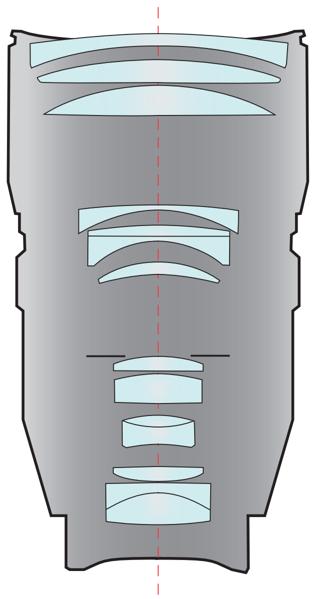
▲ This shot is a double exposure. The barrel was lit normally, and then the glass was illuminated in darkness with a near-ultraviolet laser. The laser caused each element to glow, making it possible to see some of the individual glass surfaces within the lens.

Modern lenses can be very complicated creatures indeed. A typical zoom lens might actually contain, say, 22 separate lens elements, carefully arranged in over a dozen groups. And that's not even counting the electronics, motors, and precision mechanisms used to control focus and other features.

Block diagrams

Lens designs are often depicted using flat block diagrams such as the one to the right. They indicate the shape, size, and position of each lens element, in cross-section, inside the lens assembly. They're not accurate enough to serve as lens blueprints but instead provide a general graphical description. This is the block diagram for the Zeiss Vario-Sonnar lens seen on on the previous page.

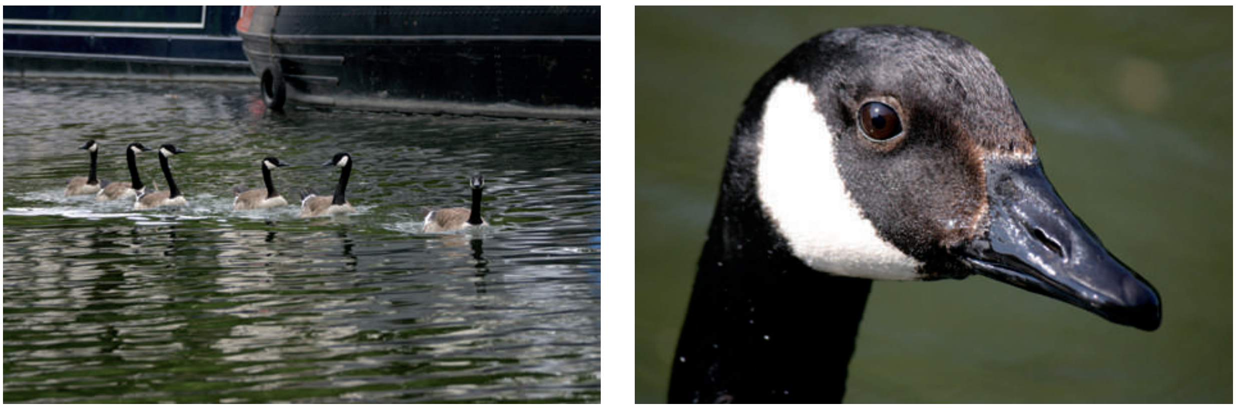
The reason behind the different shapes taken on by lens elements is described in chapter 8.



2.5 Field of view

The field of view, or how much of a scene the lens can take in, is the most important optical consideration to any photographer. After all, we've all had experiences like the following examples:

▲ You're trying to take a photo of some friends in a restaurant, but you just can't fit everybody in. You can't step back because there's a wall in the way, so your friends have to squeeze in closer. In short, the field of view provided by your lens isn't *wide* enough. The solution? A lens with a wider field of view gets everybody in the frame, as seen in the second image.

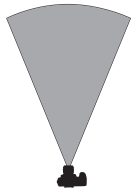


▲ The reverse can also happen. Let's say you want to take a closeup portrait of a passing Canada goose. You grab your camera but end up with a whole scene featuring some distant birds. It looks nice, but isn't what was intended because the lens isn't *long* enough. By using a longer lens you can get amazing detail on the goose's face, as seen in the second shot.

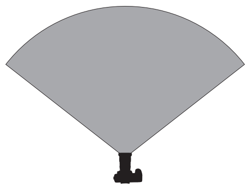
There are three rough categories of lenses when it comes to how much of a scene they can take in:

- A *normal,* or standard, lens takes in a field of view that seems natural to a person. Think of normal lenses as being good for taking pictures in close proximity to a subject, like a picture of a person standing in an ordinary room (but not traditional portraits).

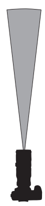
- A *wide-angle* lens can take in a large area of a scene. This can be used for photographing sweeping panoramic landscapes or large areas of a room.
- A *telephoto* lens (also referred to as a *long* lens) provides a view like using a telescope: it narrows down what can be viewed in a scene or makes a distant subject seem closer than it really is. Portrait lenses, for example, are traditionally short telephotos.



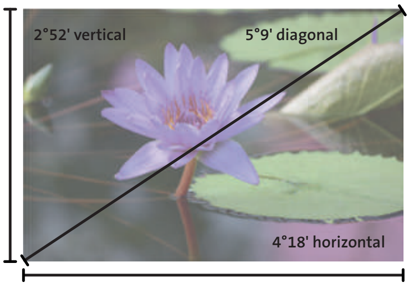
◀ This normal view shows a path winding through the Sagano bamboo forest near Kyoto. Sagano Arashiyama, Japan.
50mm lens on a full frame camera.



◀ An extreme wide-angle view looking upwards shows the beautiful canopy of bamboo stretching overhead.
17mm lens on a full frame camera.



◀ A telephoto view compresses the apparent perspective between each plant, giving the impression of a wall of bamboo canes.
200mm lens on a full frame camera.



▲ The field of view can be described as horizontal degrees, vertical degrees, or diagonal degrees of coverage. Typically, the diagonal field of view is used. This photo of a flowering water lily in the Waterlily House, Kew Gardens, England, was taken with a 300mm lens on a 1.6x subframe camera. This accounts for its very narrow field of view.

One might think that lenses would be described by the number of degrees of view possible. So a really wide lens might take in, say, 120 degrees of a scene, while a telephoto might take in only 10 degrees. Such a view could be calculated by taking a simple protractor from a school geometry set and measuring how much of the scene, from edge to edge, is visible. But for important technical and historical reasons, the field of view of a lens is usually measured by something a bit more obscure—the focal length.

2.6 Focal length

Every lens has an optical property called the *focal length,* which is measured in millimeters. The focal length is key to how much of a scene a lens can view.

If a lens has a very *short* focal length, then it's a wide angle lens. A lens with a really *long* focal length is a telephoto lens.

So why is the focal length used rather than the angle of view? The amount of a scene that a lens can view, assuming the lens is focusing on infinity, actually depends on two basic factors:

- The focal length of the lens, which determines the amount of the scene projected onto the image area
- The size of the image area: the film or digital sensor chip

And since the image area is a property of the camera and not the lens, it won't be marked on the lens.

WHY ARE CERTAIN FOCAL LENGTHS POPULAR?

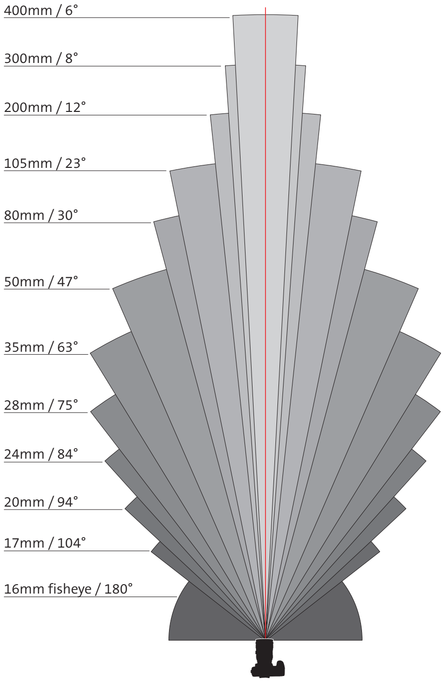
The answer is due mostly to tradition and convenience. There's no real technical reason why lenses have to be, say, 28mm, 50mm, or 85mm. And some companies do buck the trends. For example, Pentax Limited lenses have unorthodox focal lengths like 40mm, 43mm, and 77mm.

But for the sake of convenience, most makers tend to produce lenses with similar popular focal lengths.

◀ A British-built Austin Mini parked on a Paris street. By standing close to the car and using a wide-angle lens I was able to get the roof of the vehicle to dominate the foreground of the shot. Paris, France. 17mm full frame. *f*/10, 1/200 sec. ISO 100.

◀ A very long telephoto lens makes the distant moon seem very close to the prosaic sublunary scene below. Earth-shine, the reflected light of the Earth on the dark side of the crescent moon, is just visible. Death Valley National Park, CA, USA. 280mm full frame. *f*/5.6, 0.8 sec. ISO 800.

▲ Pentax has always enjoyed being different. Its standard prime lens has a focal length of 55mm, and not 50mm like almost every other manufacturer.



▲ This diagram shows the amount of coverage, in terms of degrees of diagonal field of view, for a variety of common lens focal lengths. The diagram assumes a 35mm film camera or full-frame digital SLR is being used.

The focal length of a lens isn't the same thing as its physical length. Very long telephoto lenses tend to be physically longer, but at shorter focal lengths it's not such a straightforward relationship.

2.7 But what is focal length, really?

Most photographers don't know or care about the technical definition of focal length because, honestly, it doesn't help you take photos. The focal length is simply a numeric value that describes the coverage of a lens, and with time you learn what focal length values are associated with what fields of view. If you want to explore the topic further, I have a more technical description later on in this book (see section 8.2).

2.8 Prime or zoom: adjustable focal lengths

Many lenses, known as *prime* or *fixed focal length* lenses, have a focal length that can't be changed. This is rather like the human eye. Unless we employ supplemental lenses in the form of a telescope, for example, we can't zoom in to see faraway details.

► If your camera has a prime lens, you need to physically walk around to change the field of view.

For photographers, fixed focal lengths can be a bit inconvenient or can prevent certain effects. For example, sometimes it's easy to move forward or back to take in less or more of a scene. But other times it can be dangerous or impossible—if you have to back off a cliff or into moving traffic, for example.

One solution is to pack a bag with lenses of different focal lengths and swap them out as needed. Nature photographers who work at a slow pace and carry lots of gear may take this approach. But for many of us that's a plain hassle.

◀ Four primes: 28mm, 50mm, 85mm, and 135mm lenses. All could be replaced, at least in terms of focal length coverage, with a single zoom lens with a focal length range of at least 28mm to 135mm.

Another solution is the *zoom lens,* a lens with an adjustable focal length. With a simple adjustment you can go from wide to narrow in an instant. If you can't fit all your friends in the picture, for example, you just rotate the zoom ring on the lens until they're all in there. Or if that bird is too far away, you rotate it the other way to zoom in closer.

IN AND OUT

Adjusting a zoom lens to a longer focal length for a narrower field of view is known as *zooming in*. Adjusting to a shorter focal length for a wider field of view is known as *zooming out*.

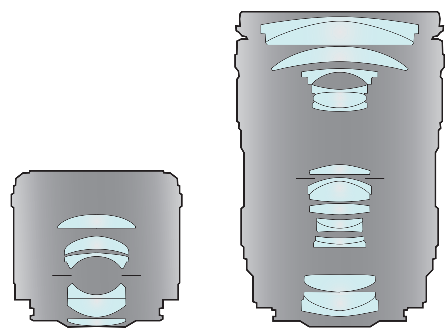
Note one common misconception: a lot of people think zoom lenses are used for taking photos of distant objects. That's actually a telephoto lens.

Why primes?

Zooms are so convenient that the obvious question arises: why do primes exist at all? Why aren't all lenses zooms?

The reason is that adjustable focal lengths bring certain optical compromises. It's simply more complicated to construct a zoom than a prime, and zooms usually contain more pieces of glass.

If you want the sharpest, most crisp images possible, then a high quality prime lens can offer better pictures than many zooms. Low-light photography also benefits because it's much harder to build a zoom lens that lets in as much light as a prime. And zooms tend to be larger and heavier than primes.



▲ A Canon 50mm 1.8 lens (left) has only six lens elements and a very simple, inexpensive design. The Canon 24–105 4L IS USM (right), however, has three times as many elements and is much more complex. Its size, weight, and price go up accordingly.

▲ “Pancake” lenses are very thin and flat lenses, and are almost always primes. This Nikon 45mm pancake is so thin that its clear protective filter (52mm in diameter) forms a significant part of its height.

Some crusty old photographers also argue that using prime lenses is very important for novice photographers because it forces them to learn about the importance of focal lengths and perspective (though to be honest, this argument sounds a bit “if it was inconvenient enough for me it’s good enough for you” to me).

Lens choice and compromises

Lens construction is thus always about trade-offs. You may want a lens that’s small and lightweight, has zoom capabilities, lets in lots of light, is really sharp, has high contrast, doesn’t distort the image, and is cheap. But in real life, you can get only some of those properties in one lens. Sadly, it’s impossible to get all of them at once.

Most amateurs on a budget choose the flexibility of low-cost zoom lenses over picture quality as their compromise. Some advanced amateurs choose the higher picture quality of affordable primes as theirs, despite the inconvenience. And many professionals select heavy and expensive high-end zooms as theirs. The best choice for you depends on your priorities.

► From left to right: a low-cost zoom, an affordable prime, and a high-end zoom.

2.9 The 35mm focal length equivalent

You’ve probably noticed a lot of lenses described in terms of their 35mm focal length. What does this mean?

This doesn’t refer to a focal length of 35mm but to a type of film. The most successful film format ever is 35mm film—strips that are 35 millimeters in width and rolled into cylindrical canisters, as shown to the left. Photographers have used cameras with image areas exactly 24mm tall by 36mm wide since the 1930s.

This extremely popular image area led to a common understanding among photographers as to the effect of focal lengths. Everyone knew that

28mm was a mild wide-angle lens, say, or that 200mm was a moderately long telephoto. Focal length numbers became a simple shorthand for field of view.

But it's important to remember that these familiar associations between specific focal lengths and coverage areas are only true when 35mm film is used.[1] Different relationships hold with different sizes of film or image sensors.

Still, it was a useful convention for many decades since 35mm SLRs were the only affordable cameras with interchangeable lenses on the market.

2.10 Digital versus film: the cropping factor

Things became more complex with the widespread use of interchangeable lens cameras that don't use 35mm film. A digital camera with a tiny sensor will cover less of a scene than a 35mm film camera would, given the same lens. Suddenly, this well-understood shorthand—of a certain focal length lens covering a certain area—became confusing.

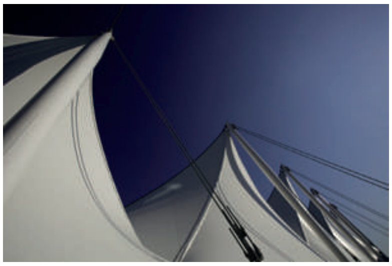
▲ The camera on the left has a "full frame" image sensor that's the same size as 35mm film: 36 × 24 mm. The camera on the right has a "subframe" sensor that's about 22 × 15 mm in size.

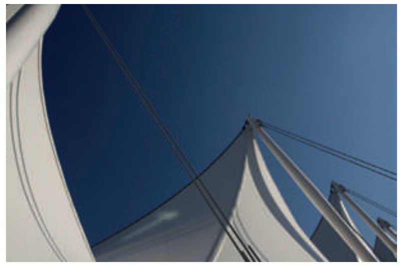
While the focal length of a lens is a critical factor in determining the field of view, it's definitely not the only one. As mentioned earlier, the physical dimensions of the film or sensor are essential as well.

To illustrate this point, imagine a photo printed onto a big piece of paper. Now imagine taking a pair of scissors and cutting off a bunch of paper around the edges, resulting in a smaller picture. The same identical lens, or same focal length, was used to take each shot. But the first picture takes in a lot more of the scene than the second, cropped, shot.

1 I'm ignoring half-frame 35mm cameras, like the Olympus PEN of the 1960s, here. These used 35mm film but with reduced image areas, resulting in different focal length relationships.

It's exactly the same thing with cameras. A lens, when used on a camera with a big image sensor, might function as a wide-angle lens, taking in lots of a scene. But the same lens, when fastened to a different camera with a smaller digital sensor, might seem considerably less wide. This is known as a *cropping factor.*





▲ This photo of Canada Place in Vancouver demonstrates how using a camera with a small-sized or cropped sensor is like trimming down a photo.

▲ The unbelievably ornate dome of Siena's Duomo cathedral, Siena, Italy. A 17mm wide-angle lens on a full-frame camera takes in a broad and dramatic view. Siena, Italy. 17mm, full frame. *f*/6.3, 1 sec. ISO 200.

▲ The same 17mm lens on a cropped-sensor camera loses a lot of information around the edges. You'd need an 11mm lens to take in the same scene.

► Of course, it's not all bad. A crop frame camera also increases the reach of a telephoto lens, letting you take photos of objects farther away. Here a 300mm lens was used with a 1.6x camera, giving the same field of view as a 480mm lens on a 35mm camera. This extremely long lens reveals distant "fairy chimneys" one stormy sunset. Göreme, Cappadocia, Turkey.

Focal length equivalence

Some lens makers describe their lenses as having a certain "focal length equivalence." This arguably confuses things because the focal length doesn't actually change at all. Instead, because of the cropping factor, the field of view will be different if a small sensor is employed. Such cameras are commonly known as *subframe* cameras, versus *full-frame* SLRs, which have the same sensor size as 35mm film.

◀ This lens, designed for a Micro Four Thirds subframe camera, actually has two sets of focal lengths printed on it: the real focal-length range and, in larger type, the full-frame focal-length range that would yield the same coverage area. To me this seems like a great way to confuse customers.

▲ This Panasonic Lumix camera has a small Micro Four Thirds sensor, meaning it has a cropping factor of about 2x compared to 35mm film.

The cropping factor

The size of a digital sensor, when compared to 35mm film, is sometimes expressed as a number, such as 1.5x. The idea behind this "focal length multiplier" is that you take the focal length of the lens, multiply it by the cropping factor, and wind up with the focal length of the same coverage as when used with 35mm film.

Consider this traditional diagram of various popular sensor sizes and their cropping factors relative to 35mm film.

◀ These boxes depict actual sensor sizes

Full-frame or 35mm film camera	Black	1x
Canon EOS 1D to 1D IV	Light blue	1.3x
Nikon DX, Sony Alpha, Samsung NX	Yellow	1.5x
Canon EOS EF-S	Red	1.6x
Four Thirds/Micro Four Thirds	Green	2x (approx)
Nikon 1/CX	Purple	2.7x
Pentax Q/many point-and-shoots	White	5.5x (approx)

Of course, when actually using a camera you don't need to do all this arithmetic in your head. What you see through the viewfinder or on the preview screen is what you'll get. These cropping factors are only important when comparing the field of a view of a lens on a full-frame camera versus the same lens on a subframe camera.

▲ APS film cartridges.

2.11 APS-C

The Advanced Photo System (APS) was a film format introduced in 1996. The idea was to create user-friendly and compact cameras, but the film was more expensive than 35mm and offered few advantages. APS was finally killed by the rise of digital.

▶ Sony E-mount cameras, such as this NEX model, employ sensors roughly APS-C in size.

However, one aspect of APS still lives on in terms of digital sensor naming. APS supported three film frame sizes, of which APS-C was most popular. The 1.5x and 1.6x subframe digital SLR cameras employ digital chips of roughly the same size as a frame of APS-C film, which was 25.1 × 16.7 mm.

2.12 Medium format

The discussion so far has been about 35mm film and equivalent image sensor sizes, but what about other types of film?

Medium-format (MF) film is usually 6 centimeters wide and offers much higher image quality than 35mm film. Hasselblad, Mamiya, Rollei, and Pentax are well-known camera makers in this market.

MF-sized digital cameras, and add-on camera backs for film cameras, are so costly that they're restricted mainly to commercial and fine art photography. Phase One and the major MF camera makers all make such products.

Common digital sensors are 48 × 36 mm or 54 × 40 mm in size, compared to MF film frames, which can be 56 × 42 mm (645), 56 × 56 mm (6 × 6), or 56 × 70 mm (6 × 7) in size, so the crop factor applies here too.

There are also large-format film cameras, which usually employ massive sheets of film 4 × 5 inches or 8 × 10 inches in size. There's even the staggeringly huge 20 × 24 inch Polaroid format, though only six of the original filing cabinet-sized cameras still exist.

Medium and large formats are not the primary focus of this book, however. So any references to *full frame* or *subframe* in this book are relative to 35mm film only.

▲ Medium-format (MF) film.

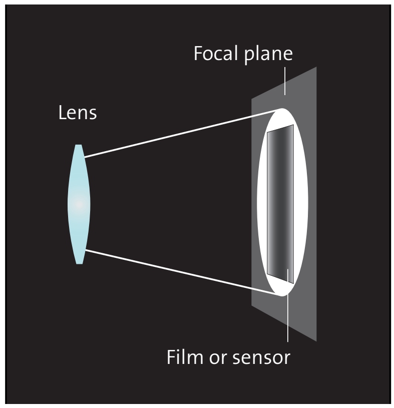
2.13 Focal length examples

It can be difficult to understand the relationship between the focal length and the field of view of a scene, so the next two pages contain a series of comparative shots. They were all taken from the same location in Vernazza, Cinque Terre, Italy. Everything used for the shots was identical except for the focal length used.

The first two shots were taken with circular and full-frame fisheye lenses (see section 5.3), respectively. The rest were taken with normal "rectilinear" lenses (see section 8.12). Each shot is marked with the focal length required to take in the scene, given a full-frame 35mm camera; a 1.5x crop camera like a Nikon DX, Pentax digital, or Sony Alpha APS-C model; or a 1.6x crop camera like a Canon EF-S model.

2.14 Image circles

Projectors shine images onto screens in darkened rooms or movie theaters. Cameras work in a similar way. They take light from the outside world, pass it through a lens, then project the final image onto the film or digital image sensor inside the darkened chamber of the camera body.



This projected image has a circular shape with most lenses and so is called the *image circle*. The projected image circle has to be big enough to cover the whole imaging area comfortably or else black areas can appear in the corners.

A coverage problem can occur when a lens with an image circle designed for a small image area is used with a larger image area. For example, Nikon subframe DX lenses have the same physical lens mount as full-frame FX lenses. So if you attach a DX lens to a camera with full-frame capabilities, you can end up with the coverage problem. It does depend on the camera and lens, though. Nikon FX cameras can detect compatible DX lenses, and can automatically crop the image down to avoid the black areas if set to do so, but they aren't able to do this for all lenses.

▶ This can be what you get if you put a subframe lens on a full-frame camera that doesn't crop automatically. The Capitol, Dougga, Tunisia.

This chart lists the focal lengths needed to achieve the fields of view depicted. The focal lengths given are for full-frame cameras (35mm equivalent), 1.5x crop cameras, and 1.6x crop cameras.

180° vertical, fisheye
Full-frame: 8mm circular fisheye
1.5x crop: 4.5mm circular fisheye
1.6x crop: 4.5mm circular fisheye

180° diagonal, fisheye
Full-frame: 15mm full-frame fisheye
1.5x crop: 13mm full-frame fisheye
1.6x crop: 13mm full-frame fisheye

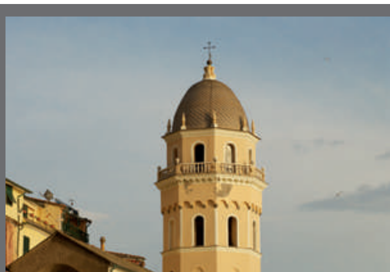
104° diagonal, extreme wide angle
Full-frame: 17mm
1.5x crop: 11mm
1.6x crop: 11mm

63° diagonal, wide angle
Full-frame: 35mm
1.5x crop: 23mm
1.6x crop: 22mm

57° diagonal, standard
Full-frame: 40mm
1.5x crop: 27mm
1.6x crop: 25mm

47° diagonal, standard
Full-frame: 50mm
1.5x crop: 33mm
1.6x crop: 31mm

23° diagonal, telephoto
Full-frame: 105mm
1.5x crop: 70mm
1.6x crop: 66mm



17° diagonal, telephoto
Full-frame: 140mm
1.5x crop: 93mm
1.6x crop: 88mm

12° diagonal, telephoto
Full-frame: 200mm
1.5x crop: 133mm
1.6x crop: 125mm

94° diagonal, extreme wide angle
Full-frame: 20mm
1.5x crop: 13mm
1.6x crop: 12mm

84° diagonal, wide angle
Full-frame: 24mm
1.5x crop: 16mm
1.6x crop: 15mm

75° diagonal, wide angle
Full-frame: 28mm
1.5x crop: 19mm
1.6x crop: 18mm

37° diagonal, short telephoto
Full-frame: 65mm
1.5x crop: 43mm
1.6x crop: 41mm

30° diagonal, short telephoto
Full-frame: 80mm
1.5x crop: 53mm
1.6x crop: 50mm

27° diagonal, telephoto
Full-frame: 90mm
1.5x crop: 60mm
1.6x crop: 56mm

9° diagonal, telephoto
Full-frame: 280mm
1.5x crop: 187mm
1.6x crop: 175mm

8° diagonal, extreme telephoto
Full-frame: 300mm
1.5x crop: 200mm
1.6x crop: 188mm

6° diagonal, extreme telephoto
Full-frame: 400mm
1.5x crop: 267mm
1.6x crop: 250mm

Canon took a different approach with its EF-S line of subframe lenses. While EF-S cameras can also accept EF lenses, EF-S lenses can't physically mate with EF-only full-frame cameras, thereby avoiding this problem.

► A Canon EF lens (left) and an EF-S lens (right). The EF-S lens has an additional projection at the end, so it cannot be used with an EF-only lens mount. Note that this particular EF-S lens has a plastic mount, though many EF-S lenses have metal mounts.

2.15 All about apertures

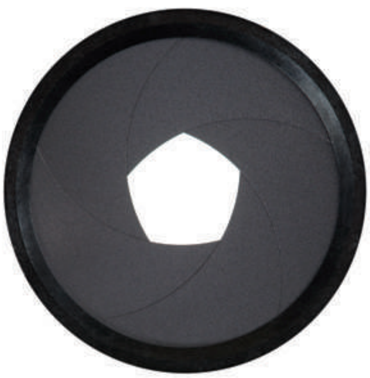
If you're ever able to see the eyes of a person in near darkness, you'll see a huge dilated pupil ringed with a tiny bit of iris. Yet the same eye in bright sunlight will be mostly iris with a tiny speck of black pupil.

The iris, or colored part, of the eye is a muscular mechanism that can open up to let in lots of light or close down to restrict the amount of light coming in.

Most camera lenses have a surprisingly similar mechanism, though one rather less beautiful than an iris. Lenses have diaphragms, which can open or close to create large or small openings called *apertures*.

The size of the aperture controls *how much* light enters the lens and strikes the film or sensor. The aperture is not used to determine the length of an exposure of a photo by blocking light—that's the shutter's job. The aperture is about quantity, not duration.

This may seem a bit odd. After all, why go to all that trouble building a lens capable of sending every possible photon of light through, then stick a mechanism in the middle to block light? There are several reasons:



▲ The diaphragm mechanism is like the iris, and the aperture is like the pupil.

- Just as with the human eye, if your scene is too bright you need some way of restricting the amount of light flooding in. You can do this by setting a fast shutter time, adjusting the camera's ISO setting (or using slower film), or sticking a dark filter over the lens. But a simple adjustable aperture is by far the most convenient way to do it.
- Many optical problems with lenses can be minimized by making the aperture smaller. Most lenses, in fact, tend to be slightly sharper when the aperture is set to a middle setting like *f*/8 or *f*/11. Shooting with a lens wide open maximizes low-light capabilities but also tends to decrease performance. See chapter 8 for more about *aberrations*.
- The amount of a scene that's in focus is affected by the aperture setting. This is known as *depth of field,* and section 2.21 is dedicated to that.

SHUTTERS

Though uncommon, a handful of cameras actually use the same mechanism as both lens diaphragm and shutter. The Pentax Auto 110 SLR of the 1970s is one such camera.

Most SLRs have shutter mechanisms, called focal plane shutters, built right into the camera body. However, some medium- and large-format cameras position a shutter inside the lens, which is known oddly as "between the lens."

Finally, some digital cameras lack shutter mechanisms altogether and just turn the sensor on and off. This is known as an "electronic shutter."

2.16 F-stops

The very first lenses lacked easily adjustable apertures. But in the mid 1800s British astronomer John Waterhouse (1806–1879) created an invention now named after him—the Waterhouse stop. These were simple metal plates that were inserted into slots in the lens barrel. Each plate had a different sized hole.

Today's self-contained diaphragms are more convenient than a bag of metal plates, but the settings are still known as stops. More accurately, a lens aperture is known as its *f*-stop (the *f* is traditionally italicized for good looks).

Apertures are described numerically, with small numbers referring to large apertures (a big hole = lots of light coming in) and large numbers referring to small apertures.

This system may seem very weird, but it has a technical logic behind it. Basically, each *f*-stop is actually a ratio. This is why lens aperture settings are often written as, for example, 1:1.8 or 1:5.6. And the ratio is as follows:

the focal length of the lens (hence the *f*) divided by the aperture diameter

Here's the traditional sequence of *f*-stops found on most 35mm cameras and digital SLRs: 1.0 1.4 2.0 2.8 4.0 5.6 8.0 11 16 22 32.

f/1.4 *f*/2 *f*/2.8 *f*/4 *f*/5.6 *f*/8 *f*/11 *f*/16 *f*/22

Not every aperture value listed here is possible with each given lens. This is just a range of possible apertures.

A traditional point of confusion is that the aperture size gets smaller as the number gets bigger. This is a bit like fractions, which get smaller as the denominator gets bigger. For example, 1/2 is bigger than 1/32.

▲ This Voigtländer lens from the 1850s is equipped with slot for Waterhouse stops. A stop's rectangular tab can be seen protruding from the side of this lens.

STOPPING DOWN

"Stopping down" a lens refers to adjusting the lens from a large aperture setting (say, *f*/4) to a smaller one (say, *f*/11). The reverse is called "opening up," never stopping up.

T-STOPS

f-stops aren't the only way to describe how much light passes through a lens. The apertures for lenses used in moviemaking are described in terms of T-stops. The *T* stands for *transmission*.

Since different lenses pass different amounts of light (number and type of lens elements, type of coating, etc.), each cinema lens (see section 8.25) is measured and calibrated at the factory. T-stops involve absolute measures of light, whereas *f*-stops involve relative measures of length.

Knowing the light-absorbing characteristics of each lens is particularly important to cinematographers when multiple cameras with different lenses are used to record the same scene simultaneously.

A mathematical diversion

But where does this odd range of numbers come from? Why is there this seemingly random set of aperture settings? Why isn't it just a sequence like 1, 2, and 3?

Aperture sizes are based on the biology of the human eye. We don't see changes in brightness in a linear fashion (1, 2, 3, 4). We actually sense changes in light brightness—and sound levels for that matter—in a roughly logarithmic fashion (2, 4, 8, 16).

The aperture range represents a halving of brightness for each decrease by one stop. To halve the brightness, you halve the area of the aperture opening. And that means you multiply the diameter of the aperture circle by the square root of 2.

So you start with a maximum theoretical aperture of *f*/1 and multiply each *f*-stop by the square root of 2, which is about 1.4. The numbers are then rounded up for convenience, and you get the scale listed earlier.

HALF AND THIRD STOPS

There are two common ways of subdividing the number of stops on a lens: half and third stops. Which is better is simply a matter of preference, and many cameras allow you to choose.

Since these settings apply to shutter speed increments as well, they're sometimes referred to as exposure values (EVs) rather than stops.

2.17 Maximum apertures

Another key property of a lens is the largest aperture setting that it's capable of. This value, the *maximum aperture,* is important for a number of reasons.

Why lenses with large maximum apertures are desirable and expensive

If you've ever priced out lenses with similar specifications except for the maximum aperture, you'll notice a huge difference in cost. Even seemingly small differences in maximum aperture can result in massive price disparities. For example, the list price of the Canon 85mm 1.2L is about five times that of the Canon 85mm 1.8. There are a number of reasons for this.

▲ Two Canon 85mm lenses. The left lens has a maximum aperture of *f*/1.8, and the right lens has a maximum aperture of *f*/1.2.

- At large apertures a small difference in numerical values can actually represent a big difference in actual aperture. *f*/1.2 (right) doesn't sound like it's much bigger than *f*/1.8 (left), but as this photograph shows, there's a noticeable increase in light-gathering capacity.
- It's often necessary to employ exotic glass or complex manufacturing techniques to produce a very "fast" lens (see section 2.18).
- Fast lenses are typically marketed to experienced photographers, which means that they tend to be built to a high standard. They may have sturdy metal barrels, weatherproofing, advanced electronic features, and other features that add to the cost. They are sold in low volumes, though usually with high profit margins.

There is one exception here: standard primes. It's not that difficult to build a fairly fast lens when standard focal lengths are involved, especially if the lens is a prime lens. For this reason, 50mm primes are commonly available as *f*/1.4 and *f*/1.8 lenses, and they can be fairly cheap (see section 5.4).

With modest increases in cost 28mm and 85mm lenses can also be available as *f*/1.8 models. But anything longer or shorter than that tends to involve big price jumps.

▲ A standard Nikon 50mm *f*/1.4 lens.

Constant versus variable aperture zooms

There are two basic types of zoom lenses when it comes to maximum apertures. Most affordable zooms have *variable apertures,* meaning they have a larger maximum aperture when at the short end of the range than at the telephoto end.

▲ A consumer lens with variable maximum apertures, ranging from *f*/3.5 to *f*/4.5.

▲ A professional lens with a fixed maximum aperture that's *f*/2.8 all the way along the focal length range.

▲ A fairly fast 50mm *f*/1.4 lens by Sigma.

A typical consumer zoom, for example, may vary from *f*/3.5 at the wide end to *f*/5.6 at the long end.

However, more expensive lenses may have *constant apertures,* which means that the maximum aperture stays the same throughout the zoom range. The most expensive zoom lenses tend to have a maximum aperture of *f*/2.8 across the range (see section 2.8). A slightly less costly lens might have a maximum aperture of *f*/4 across the range.

Constant aperture zooms are more expensive to buy for the simple reason that they're more expensive to make. More advanced optical engineering is required to have the same aperture range throughout. This also means that such lenses are aimed at the professional market.

These should really be called constant maximum aperture and variable maximum aperture lenses, but the word *maximum* is usually dropped.

2.18 Fast and slow lenses

These are commonly used terms—some lenses are said to be *fast* and others *slow*. While this may sound like a reference to the speed of their autofocus motors, the terms actually refer to the amount of light a lens can let in.

A "fast" lens can let in lots of light when its aperture is wide open so that relatively brief, or "fast," shutter times can be used. A prime lens with a maximum aperture setting of, say, *f*/1.2 or *f*/1.8 would be considered fast. A fast zoom might have a maximum aperture of *f*/2.8.

A "slow" lens is not able to let in as much light, thereby requiring longer, or "slower," shutter speeds. A lens with a maximum aperture of *f*/4 might be considered to be slower. Maximum *f*/5.6 or *f*/8 would be very slow.

Lens speed matters for three basic reasons:

- Fast lenses can help you take sharper photos in low-light conditions by allowing shorter exposure times.
- Since it's more expensive to build a fast lens, such products tend to be of higher quality and pitched more to the professional market.
- Fast lenses let in lots of light, meaning a brighter view in an optical viewfinder. They also improve autofocus speed.

Is that lens fast or slow?

On 35mm or full-frame cameras, the nearer a lens focal length is to 43mm (the diagonal of the image area), the easier it is to construct as a fast lens. Thus 50mm prime lenses tend to have large maximum apertures. The wider or longer the lens gets, the more expensive it is to make it fast.

Zoom lenses are similarly affected, though the problem is even more pronounced since it's more difficult to build a fast zoom than a fast prime. For that reason, a standard zoom with a range close to 43mm is easier to build as a fast lens than is a wide angle or telephoto zoom. And a zoom lens with a big focal length range is even less likely to be a fast lens.

SPEED DEMONS

There have been a handful of insanely expensive lenses that have attained *f*/1 or faster. The discontinued Canon EF 50mm 1.0L was the fastest 35mm SLR lens ever, and autofocus to boot. For manual-focus rangefinders, there are the Leica Noctilux-M 50mm 0.95 ASPH and the Canon S-mount 50mm 0.95 of the 1960s. But most amazing of all was the Zeiss 50mm 0.7, originally built for NASA research and later used by director Stanley Kubrick.

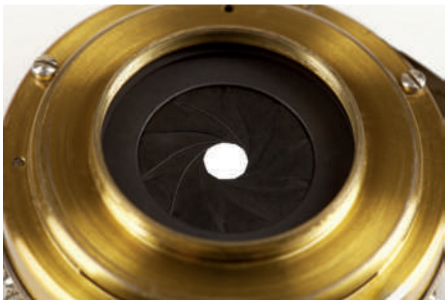
▲ Kubrick was legendary for pushing the limits of technology in service of his filmmaking. In the case of his 1975 period film *Barry Lyndon*, Kubrick wanted interior scenes lit solely by candlelight, just as they would have been in the eighteenth century. This was considered impossible at the time, owing to the slowness of the film emulsions available. Undeterred, he located some Zeiss Planar *f*/0.7 still-photography lenses, from a small batch built for NASA, and had them adapted for use with a heavily altered Mitchell BNC movie camera. The resulting candlelit scenes were extremely challenging to film (see depth of field, section 2.22), but are also some of the most memorable scenes in the movie.

Shown above is one of the Kubrickified Zeiss Planar lenses, along with surviving double-wick candles originally made for the film. From the Stanley Kubrick Archive, courtesy producer Jan Harlan.

Here's a table outlining the sort of maximum apertures you can expect for different focal lengths.

Focal length	Typical aperture	Fast lens	Very fast lens
20mm	2.8	2.8	
28mm	2.8	1.8	
35mm	2.0	1.8	1.4
50mm	1.8	1.4	1.0–1.2
85mm	1.8	1.4	1.2
135mm	2.8	2.0	
200mm	2.8	2.0	
300mm	4	2.8	

2.19 Diaphragms



▲ The diaphragm mechanism from an antique all-manual lens.

Diaphragms are thin overlapping metal or plastic blades that rotate in or out, changing the size of a hole—the aperture—at the center. The number and shape of these blades determines the physical shape of the lens aperture.

An interesting effect related to the construction of the diaphragm involves stars that appear around high-contrast points, like bright light sources at night. When a lens is stopped down to a small opening, diffraction effects (see section 8.22) create little stars. Odd numbers of blades result in double the number of rays; even blades result in the same number of rays because each ray is doubled up.

The roundness of the aperture also has an effect on the optical property known as *bokeh* (see section 9.8).

► Seeing stars: aperture-induced rays around point light sources. Little Venice, London, England. 24mm full frame. *f*/19, 30 sec. ISO 400.

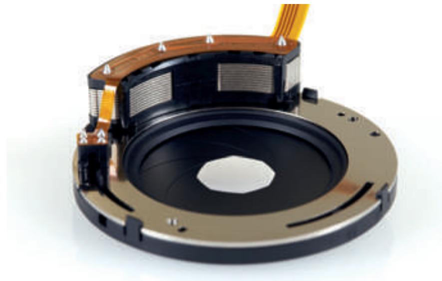
2.20 Adjusting the aperture

The method for adjusting the aperture diaphragm depends on the camera and lens used. For many years the traditional means was an adjustable ring in the lens barrel. Turn the ring one way to stop down; turn it the other way to open up. A simple mechanical linkage.

However, since the introduction of Canon EOS in 1987, camera makers have been installing electric diaphragm control motors inside lenses and discontinuing the manual aperture rings. Such lenses have aperture control on the camera body itself, typically in the form of a rotating thumbwheel.

These "electromagnetic diaphragms" can sometimes cause compatibility issues. In the case of Canon EOS, all EF lenses have aperture motors and all cameras have aperture control, so there's no problem. But in the case of Nikon, for example, a G lens with no aperture ring can't be easily used by an older film camera with no electronic aperture control. Some Pentax lenses and cameras can be similarly affected.

The reverse is also true. Some newer low-cost Nikon, Pentax, and Sony DSLR cameras require a lens with an aperture motor. These cameras aren't able to adjust the aperture setting of older lenses that lack such motors. Check your user manual for details.



▲ A typical computer-controlled diaphragm from a modern camera lens. The raised section festooned in ribbon cables is a housing for the "stepper" motor.

2.21 Wide-open metering

If you've ever peered into a lens, you may have noticed that the diaphragm isn't always visible. Why is this?

Most cameras do their metering with the diaphragm wide open. This also makes it easier to look through the viewfinder—things would be really dark if you happened to be using a small aperture setting.

Then, when the camera's shutter release is pressed, it rapidly stops the lens down to the predetermined aperture, takes the photo, then springs the aperture right back to the wide-open position again. This is so quick it's nearly imperceptible.

This Canon DOF preview button ▲ (above) is an unmarked button next to the lens mount, whereas this Pentax DOF control ▼ (below) is built into the spring-loaded on/off switch by the shutter release button.

Depth of field preview

Many cameras have a way of stopping the lens down without taking a photo. This is the depth of field (DOF) preview button, often located somewhere near the lens mount.

Pressing this button closes down the lens aperture to whatever setting you've preselected. This will result in a darkening of the view through the viewfinder if a small aperture is selected. Try this and look through the front of the lens to see the lens diaphragm mechanism springing into action.

But what's meant by the depth of field?

2.22 Depth of field

A lens can focus at only one distance at a time. So not every part of a photo can be sharp.

▶ The focus in this shot is on the champagne flute, and the background is quite blurred thanks to shallow depth of field. This is a useful photographic technique known as selective focus, which draws the viewer's eye to key sections of the scene. Hotel Everland, Paris, France. 105mm full frame. *f*/4, 1/100 sec, ISO 100.

When thinking about focus, it can be useful to imagine a vast pane of glass located at the exact distance that the lens is focused. Everything in the final photo that's situated at this imaginary pane is going to be sharp. And things far away from it will be blurry and out of focus in the photo.

The glass pane isn't a perfect analogy though. Objects situated at the glass will be sharp and objects further away won't be. But what about things in between?

▶ Of the rows of flowers, the middle row is sharp, because that's the row the camera is focused on. However the nearer and farther flowers are very much out of focus. Keukenhof gardens, Lisse, Netherlands. 300mm 1.6x subframe. *f*/5.6, 1/500 sec. ISO 100.

The answer is that there isn't a sharp transition point between things that are in focus and things that aren't. Instead, there's a gradual gradient between the two. There's no way of saying what's truly in focus and what isn't within that gradient. There's a range where things are more or less acceptably in focus compared to the sharpest point. The transition between sharp and blurry is subjective.

This area of acceptable focus in our photo is known as the *depth of field*. A photo with a narrow range of acceptable focus has a *shallow* or narrow depth of field. Conversely, a photo where lots of things are acceptably sharp, even objects fairly far from the plane of focus, has a *deep* or wide depth of field.

Numerous factors determine how deep or shallow the depth of field is going to be.

Aperture and depth of field

The size of the aperture is one of the main depth of field determinants. A large aperture—the lens is wide open—will result in narrower depth of field. A small aperture—the lens is stopped down—will result in a deeper depth of field.

▲ At *f*/1.2, depth of field is incredibly shallow. Note how only one row of chess pieces is actually in focus.

▲ By stopping down to *f*/16 we ensure that most of the pieces on the board are in reasonably sharp focus.

So the aperture setting and depth of field are interrelated. This can be a problem if you want to adjust one thing without affecting the other. This is also why depth of field preview (see section 2.20) can be useful; it gives you a live and immediate demonstration of what the DOF will be in the final picture, particularly useful with digital Live View.

Image area and depth of field

The size of the recording area—whether film or a digital chip—is also key to depth of field. The larger the area, the shallower the shallowest possible depth of field and vice versa.

▶ This portrait was shot at *f*/2.8, and depth of field is so shallow that although the model's right eye is in focus, her left eye isn't.
85mm, 1.6x subframe. *f*/2.8, 1/30 sec. ISO 200.

This is one of the reasons professional portraitists with large cameras can get that beautifully razor-thin depth of field, whereas users of point-and-shoots can't. Digital point-and-shoot cameras tend to have tiny image sensors, which is one reason everything's sharp with these cameras. By contrast, shallow depth of field can be difficult to work with, but it can also yield fantastic photographs.

The Planar lens shown in section 2.17 was incredibly difficult to use because of the vanishingly thin depth of field at *f*/0.7. If you watch Kubrick's film *Barry Lyndon* you'll notice that the actors barely lean forward or back during the candlelight scenes. Had they done so they'd have gone right out of focus.

Other factors determining depth of field

Numerous other factors come into play when determining depth of field:

- The size of the image. A tiny photo on a website may appear to be acceptably sharp, but when printed in a large size, whole areas may appear to be out of focus.
- Viewing distance. A small 4x6 print viewed close up may reveal big areas that are out of focus. But if the same print is on the wall, it may seem to be acceptably sharp.

- Distance of subject to camera. A macro or closeup photo, where the subject is extremely close to the camera, will have a very narrow depth of field. On the other hand, a telephoto shot of an object far away will have greater depth of field. Here, it's the distance, not the focal length per se, that's affecting depth of field.
- Subjective perception. Since there's no objective way of assessing what's in focus and what's not, the apparent depth of field also depends on the viewer.

For further technical information on depth of field, see section 2.22.

◀ A medium-wide aperture and the fact that both model and smoke are more or less in the same plane (and thus roughly the same distance from the camera) means that most of this shot is in focus. 50mm full frame, *f*/8, 1/60 sec, ISO 100.

▶ A wide-open aperture and a fair distance between the closest and furthest pews means that focus is restricted to just one of the carvings. Fitzalan Chapel, Arundel Castle, Arundel, England. 105mm full frame, *f*/2.8, 0.4 sec, ISO 100.