Chapter 4: Modern Atomic Theory

4.1 Let There Be Light

What is light? That's a deceptively simple question. We use light every day. We rely on it for even the most basic tasks, whether we're walking through our homes or driving through the busy streets of our cities. Without light, you would be unable to read this sentence right now. But what is it?

Leave that aside for a moment and pick up a pencil. Touch it. Feel its weight in your hand. What's it made of? Wood and graphite mostly, with flourishes of metal and rubber. How did you figure all of this out? You looked at the pencil. You touched it. Perhaps, you listened to the scratching noise it made as it skidded across paper, or you smelled the cedar slivers flaking off from the end, or you even tasted it. That's how you figured out what it's made of. You examined it.

But what about light? What is it? How do you examine it? You can't grab it. You can't look at it under a microscope. You can't touch light or taste it or smell it. You can't really even see it; you just see other things with it. All that scientific inquiry you performed with your pencil works much less well when examining light. Light is simultaneously everywhere and mysterious.

And light's value extends far beyond "practical" purposes. The Dutch painter Rembrandt (1606–1669) used light in his paintings to communicate. Imagine you took a photograph of your house without any light—no streetlights, no sun or moon, no flash. The photograph would be a blank, black rectangle. Now imagine you could pick one thing to light up, and one thing only: your front doorknob. You set up the light, and you retake the picture. What will you see? You'll see a vague outline of the doorway, perhaps nothing of the house at all, and a bright doorknob. When you look at that photograph, you won't be able to see anything else. You've used that one light to emphasize what you want to draw attention to.

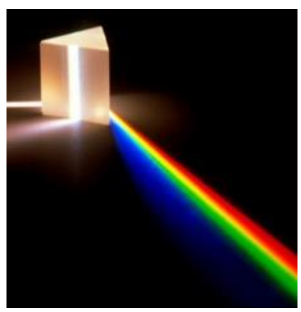
Rembrandt did something similar in his use of light. He used light to highlight what he wanted the reader to notice. For example, look at this painting. What do you notice first? Most people notice the brightest part of the painting first. Here, that's the waves on the left. So your first thought is the intensity of the storm. The focus on the splashing wave makes you almost *feel* the wetness on your skin. But that's not the only light Rembrandt uses in this scene. Look closer at the occupants of the boat: one of them is accented with light. It's Jesus, waking in the bottom of the boat, as the disciples plead with Him for help. You can barely see the disciples' faces. There's no other light near Jesus' head. Our eyes, like our hearts, are drawn to Him.

In Rembrandt's hands, light highlights the important, the striking, even the divine. Light catches our eyes because we see by means of it. Like the Scriptures show us where to focus our hearts and minds, light shows us where to focus our eyes.

As fascinating as this is, it doesn't tell us what light is. Scientists throughout history have had the same problem we did: it's difficult to isolate light in order to observe it. So instead of examining it up close, they employ a different tactic. They propose theories and then begin experiments to see how well light's characteristics match their theories. Is light made up of tiny particles of such slight mass that we cannot feel them when they strike us? If so, we ought to be able to run an experiment that demonstrates this. Or perhaps light is a wave, bouncing off whatever it strikes? Experimentation ought to reveal this.

4.2 Hide Your Light Under a Prism? No!

In the 1600s, it was common knowledge that light passing through a prism produced colored light. Scientists hypothesized that something in the prism changed the color of the light. Isaac Newton observed this colored light and was curious about exactly what happened inside the prism to change the light.



Biographical Pullout
Isaac Newton (1642–1727)

Isaac Newton was born on Christmas Day in 1642, during the English Civil War. His father died three months before he was born, and his mother remarried and left three-year-old Isaac behind with his grandmother. An uncle recognized Newton's intellect and encouraged him to pursue university studies. At Trinity College, Cambridge, Newton pursued studies in basic philosophy, mathematics, history, and science, and he voraciously read advanced physics. He graduated in 1665, intending to continue his studies.

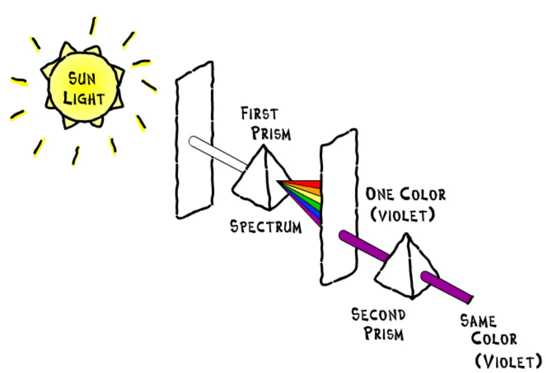
But just at that time, the bubonic plague resurfaced in England, killing an estimated 100,000 people in London alone. For the safety of its students and professors, the University of Cambridge closed for two years. Most students would have seen this as a welcome break from studying, but Newton returned home to experiment. While cloistered in scientific study, he developed the foundational ideas of calculus, hypothesized principles of light and color, and expounded on the laws of planetary motion.

Newton contributed enormously to the sciences of astronomy, physics, and chemistry, as well as to mathematics. In 1687, he published his magnum opus, *Philosophiae Naturalis Principia Mathematica*. He was knighted by Queen Anne in 1705, the second scientist (after Francis Bacon) to receive such an honor. When he died in 1727, he was buried in Westminster Abbey.

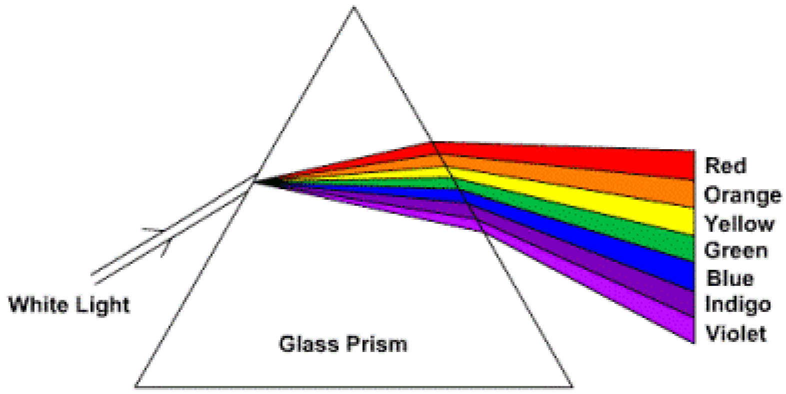
Newton was uncomfortable with the explanation that “something” happened inside the prism that made the light come out colored. He wanted to know what that “something” was. On a sunny day during the year of the Great Plague, he pulled a shade down over a window and cut a narrow slit in it. The slit was narrow enough that only one thin beam of light could pass through, after which the light traveled through a prism, landing on a screen behind it. As expected, the light that emerged from the prism and appeared on the screen had a different color. When he moved the screen farther from the prism, he could see an entire spectrum of colors. This experiment showed only that light passing through a prism produced a spectrum of colors; it did not explain what the prism was doing to make the colors appear.

Now imagine that Newton used a second prism. What would you expect to happen this time? Would the light split into yet more colors? Would the prism stop the light altogether? Would the second prism reverse whatever it was the first prism did to the light? Before you answer, reflect on what the prism is doing in the first place. Fundamentally, it’s changing the light’s direction, or **refracting** it, as the light passes from the air, through the glass, and back to the air. In the process, the prism spreads the light into its visible colors. When we pour the light through a second prism, it’s being refracted again. What would happen next?

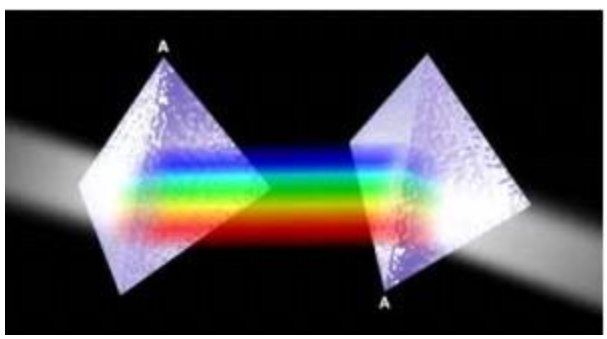
Newton decided to find out. He again cut another narrow slit, but this time in the screen where he saw the rainbow of light.



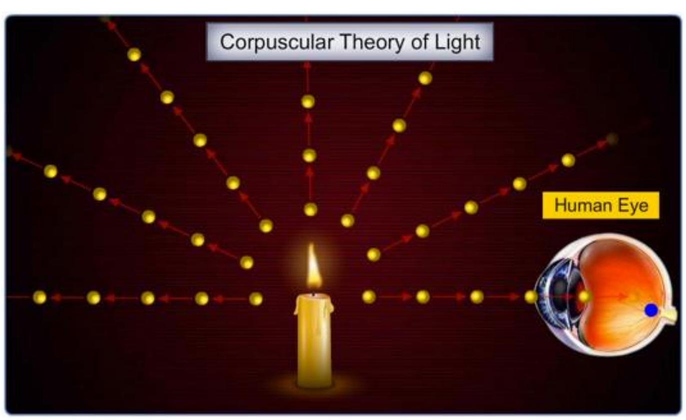
He adjusted the prism so that only the violet-colored light passed through the tiny slit in the screen. He placed a second prism on the other side of the screen and allowed the violet light to pass through that prism also. The light coming through the second prism was still violet. The prism was not changing the light at all! He concluded that the prism was simply separating white light into its colored bands. This spreading out of a beam of light we call ***disperson***, and you see it easily every time you create a rainbow with your garden hose.



Next, Newton recreated the same experiment with two prisms, but this time he placed the second prism upside-down and in front of the screen. Now, the light passed through the first prism and emerged as a colored spectrum. The colored spectrum passed through the second prism and emerged as white light again. Newton had reassembled the color spectrum into white light!

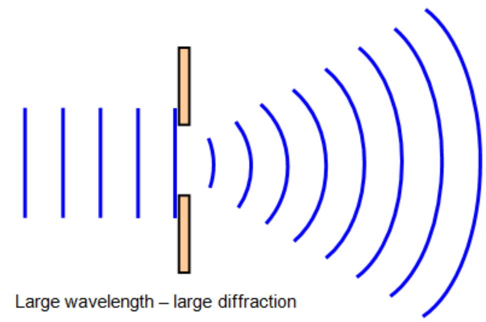


Were Isaac Newton here today, we could ask him what light really is. He would tell us, citing his 1704 book on the topic, *Optiks*, that light consists of a stream of very small particles called **corpuscles**. He believed that light's different colors arise from the corpuscles' different sizes.

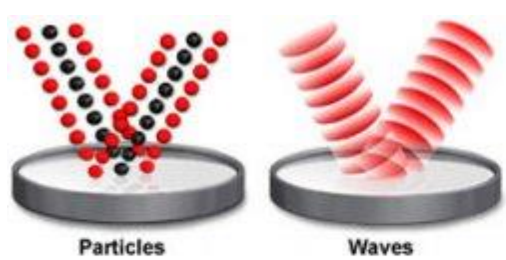


Newton would add that the material of the prism imparts a spin to the particle of light as it passes through. The spin of the particle varies, depending on the size of the particle, just as the spin a quarterback puts on a football varies, depending on the size of the football. This understanding of light is called the **corpuscular theory**.[1]

Other scientists of the day strongly disagreed with Newton's explanation of light. Christiaan Huygens /Hoy genz/,[2] a Dutch physicist, had previously conducted experiments that strongly showed that light has wave properties, since it clearly **diffracts**, or bends, as it passes through a slit.[3]



Newton squabbled with these other scientists in public, in writing, and in the scientific academies. He and his supporters believed that the scientific evidence supported the hypothesis that light was composed of a stream of particles, while Huygens and his supporters saw much evidence that light was composed of waves.



[1] Corpuscular come from the Latin *corpusculum*, meaning "a little body" or particle.

[2] The Dutch sounds closer to /How ghenz/.

[3] Be exceedingly careful not to confuse these three related terms: refraction, diffraction, and dispersion. *Refraction* is always due to the passage of light *from one medium to another*, and *diffraction* is always due to the passage of light *through a slit or around an object*. By whichever means, refraction or diffraction, *dispersion* is the separation of white light into colors.

The differences of opinion over whether light was a particle or a wave, each backed by excellent experimental data, remained unresolved at the time of Newton's death.

Once Newton showed that white light was composed of a rainbow of colors, other scientists began to investigate the properties of the different colors. Englishman William Herschel conducted an elegantly simple experiment where he measured the temperature of each color.

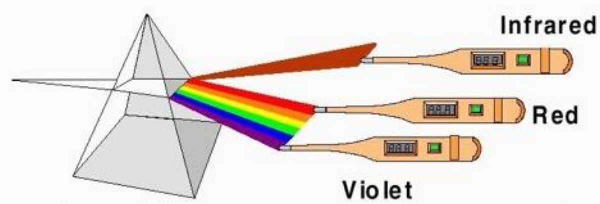
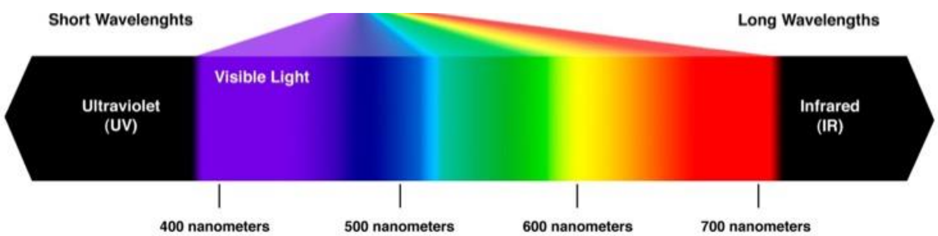


Fig. 1: Herschel used a prism and thermometers in his experiment that eventually led to the discovery of the infrared region of the electromagnetic spectrum.

The temperatures of the different colors varied slightly, but, most surprisingly, the hottest temperature was just *beyond* the red band. This was the first indication of invisible light and led to the discovery of **infrared (IR) light**. If you've studied Latin, you may remember that "infra" means "below" or "lower than." Infrared light was thought of as "below" the red color on the light spectrum.



Scientists sometime act like tracking dogs on the scent of a great discovery! No sooner did Herschel present evidence of light beyond the red band than Johann Ritter, a German scientist, set about to find light just beyond the *violet* band. Ritter shined light on a sample of silver chloride. The light induced a chemical reaction that began to decompose it. Next, Ritter shined each individual color of light on the substance. He showed that violet light was more efficient at decomposing silver chloride than red light was, but that the light just beyond violet light caused the decomposition to happen fastest. Eventually, this extra strong light came to be called **ultraviolet (UV) light**. Once again, Latin comes into play. Ultra means "beyond" or "on the other side of." Ultraviolet light is "beyond" the violet.

Other scientists discovered light beyond the ultraviolet and the infrared. In fact, the spectrum of light does not seem to end. In this regard science seems similar to light. There is always one more discovery or one more observation to be made. This is one reason scientific discovery engenders such tremendous excitement around the world.

Section Review Questions

1. When Newton passed only the violet light through the second slit and prism, the light remained violet. What did he conclude?
2. Would he have come to a different conclusion had he passed green light through the slit and prism and the light remained green?
3. Had Newton passed violet light through the second slit and prism, but it had changed colors, what might he have concluded?
4. What was the major difference between Newton's and Huygens's views of light?

Answers:

1. Newton concluded that the prism was not changing light, since the violet light passed through unchanged. He concluded that the prism separated white light into colors, but that the colors could not be further separated by a second prism.
2. No, he would have drawn the same conclusion had he used green light.
3. If the violet light passing through the second prism had changed colors, Newton might have concluded that something in the prism was indeed changing light and, perhaps, he would have continued to search for what that something was.
4. Newton saw light as a stream of differently sized particles, while Huygens viewed light as having wave properties similar to those observed in water. There was good evidence in the 17^{th} century to support both views.

4.3 The New Wave

Newton's corpuscular theory fell into disuse after his death, and the wave model of light dominated science in the 1800s. Light waves were easily produced and moderately easy to measure and study. Scotsman James Clerk Maxwell, less well-known than Einstein but equally important to modern science, showed that electricity, magnetism, and light were forms of the same sort of energy, **electromagnetic (EM) radiation**. Before Maxwell, the three were studied as separate disciplines (because thought of as separate phenomena). In the 1860s Maxwell showed that light waves, like other waves of EM radiation, are variations of electric and magnetic fields that carry energy from one place to another.

Before we go further, let's be careful not to confuse EM radiation with the radioactive decay we studied in the previous chapter. Now the exception to that general rule. There is one point of overlap worth mentioning: gamma rays. Consider gamma rays and ultraviolet light for a moment. Though both are part of the EM spectrum, they are produced by different processes and have sorely different impacts on living organisms. Even small doses of radiation from gamma rays, produced by nuclear changes in an atom, can penetrate tissue and cause cancer. The greatest risk of short-term exposure to ultraviolet radiation, however, is sunburn!

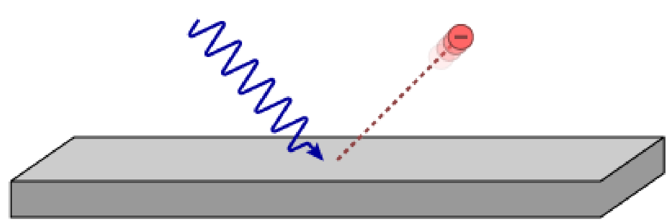
Maxwell's work almost completely solidified the scientific world's view of light; throughout the rest of the 19th century, researchers interpreted the results of their experiments from the foundational belief that light is a wave and not a particle at all. It appeared that Newton's corpuscular theory had been discarded entirely.

As scientists, we must be careful to remember that what appears proven, such as the notion that light is merely a wave, may in fact be wrong. We need to approach new evidence, and new interpretations of the evidence, with an open mind. In the early 1900s, one particular experiment stunned and confused the scientific community. Let's see if we can envision this experiment and experience a bit of the conundrum into which this experiment plunged the scientists of the day.

Imagine that you have a sheet of metal. In fact, let's say you've purchased a golden newspaper. What happens when you shine a flashlight onto it? Does the golden newspaper absorb the light's energy? If it does, does it get warmer? Or, perhaps, the newspaper merely reflects the light and nothing much else happens? Under Maxwell's theory that light was a wave of EM energy, we might expect the golden newspaper to emit, or give off, electrons. According to this new theory of light, light waves would strike some of the electrons in the gold atoms and knock them loose, sending them flying off into space.

Now imagine that you've got a flashlight with a dial on the side that adjusts the brightness of the light. Twist the dial one way, and the light grows dimmer; twist it the other, and it gets brighter, or more intense. What happens when you shine this brighter, more intense, light on the golden newspaper? If Maxwell was right, then we'd expect that the electrons that fly off would do so with greater energy. Light waves of varying intensities should emit electrons of varying energies, shouldn't they?

This is the experiment that German physicist Philipp Lenard performed in the early 1900s, minus the golden newspaper. In the experiment, called the **photoelectric effect experiment**, Lenard shined light on the surface of a metal. The light transferred its energy to electrons in the metal, and some of those energized electrons were then emitted from the surface.

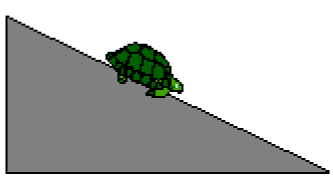


Lenard tried lights of different intensities. Based on the Maxwell wave theory of light, Lenard expected brighter light to kick off electrons that were more energetic and dimmer light to kick off electrons that were less energetic. Think of a baseball game. When a batter hits a ball hard, the ball travels quickly into the outfield as a line drive. The same batter, hitting the ball with less intensity, may send the ball only a short distance as a grounder. Maxwell thought the same was true of light. After all, it makes sense that high intensity light would transfer more energy to departing electrons than lower intensity light would.

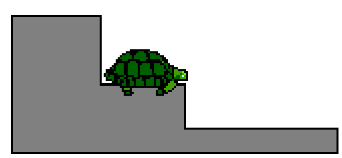
But that wasn't what happened. To everyone's surprise, no matter how intense the light, the electrons left the surface of the metal with the same energy. Think back to our golden newspaper. Lenard showed that even if you increase the intensity of the light you shine, the electrons won't absorb any more energy. Was Maxwell's understanding of light flawed?

Albert Einstein resolved the discrepancy between Maxwell's wave theory of light and the photoelectric effect observed by Lenard. In a 1905 paper, he proposed that light consists of **photons**, which are massless bundles, or particles, of light. Increasing the intensity, or brightness, of light only means that more photons are present, not that they are more energetic. Since every photon excites one and only one electron, increasing light's intensity, and therefore the number of photons present, only increases the *number* of released electrons. It does not increase their *energy*. Electrons can absorb only a set amount, or **quantum**, of energy. The photoelectric effect is the most direct and convincing evidence that light has a particle, as well as a wave, nature. Perhaps, Newton's understanding of light had been discarded too quickly.

The concept that light possesses both wave and particle characteristics turned the world of physics upside down and gave birth to a field of study called **quantum mechanics**. In classical mechanics, the kind of physics of motion that Newton practiced and studied, energy could manifest at any value you could imagine, just as the turtle in the picture can be at any point on the ramp.



Classical Mechanics
Turtle can be present
anywhere, at any value, on the ramp.

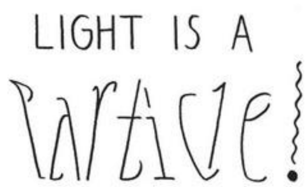


Quantum Mechanics

Turtle can be present only at certain allowable values.

In quantum mechanics, the kind of physics for which Einstein laid a foundation, small particles, like electrons and photons, can possess only certain values, or amounts, of energy. We call those values the allowable energies. To continue our analogy of the turtle, the turtle in the second picture can be on one step or another, but never in between. In quantum mechanics, similarly, the energy of small particles can be one value or a different value, but none of the values that lie between them.

So, back to our first question: what *is* light? Is it a wave? Is it a particle? Newton said it was a particle. Huygens and Maxwell said it was a wave. Einstein said it was both. Confused?



One of the exciting aspects about being a scientist is that we often don't know what the solution to a problem is, but we keep experimenting in an effort to find it. At present scientists believe that light has both wave and particle natures (or properties) at the same time—*not* sometimes a wave and sometimes a particle. Mind-blowing, isn't it? Light, whether from the sun or from a light bulb, is both a wave and a particle. We call this twin nature **wave–particle duality**. This duality concept both gave birth to the world of quantum mechanics and, as we will see in future chapters, explains the chemical bonding of atoms and molecules.

And all of that from light passing through a prism!

Devil's Advocate: Why Theorize?

The history of science abounds with theories. But what's the value of crafting a new theory? Why do scientists do it?

You might think that the purpose of a theory is to come up with a new understanding of a certain phenomenon that explains it better than current theories. If a scientist has a particularly good explanation, she might cause a major change in how everyone understands an entire aspect of the natural world. Copernicus upended how science looked at the solar system, for example, with his theory of heliocentrism. Einstein's theories about the relativity of space and time (about *spacetime*, really) produced a similar revolution.

But scientific theories like that are rare, aren't they? Not everyone develops a mental model of the world that causes a paradigm shift in our basic understanding of it. On the contrary, some scientists argue, the value of new scientific theories lies in their usefulness for revealing problems with established understandings. In this view, a scientific theory is valuable when it and its evidence or experimental data narrow the realm of possible explanations for a given phenomenon. Lenard's photoelectric effect experiment is a good example of this sort of critical, or fault-finding, usefulness. Lenard's experiments didn't so much suggest a new way to think of light as it demonstrated problems with established wisdom, and this helped later scientists investigating the cause of the photoelectric effect to narrow the field of possible explanations.

So which is it? Ought scientists to aim to develop theories that revolutionize the way we view the world, or should they set their sights, instead, on the seemingly less ambitious goal of disproving or discrediting prevailing views? The answer to that question may be the same as the answer to this: which is light, a wave or a particle?

Review questions

1. Can you think of something that when struck with more force travels with *more* force?

2. Can you think of something that when struck with more force travels with *less* force?

3. How does changing the intensity of light change the number of electrons emitted from the surface of a metal?

4. What's the difference between quantized and non-quantized energy?

Answers:

1. Sure. Many things! For example, striking a baseball with great force sends the ball faster and with more energy than would striking it only lightly.

2. It's difficult even to imagine an example in the everyday world of our experience, though it's certainly an intriguing notion!

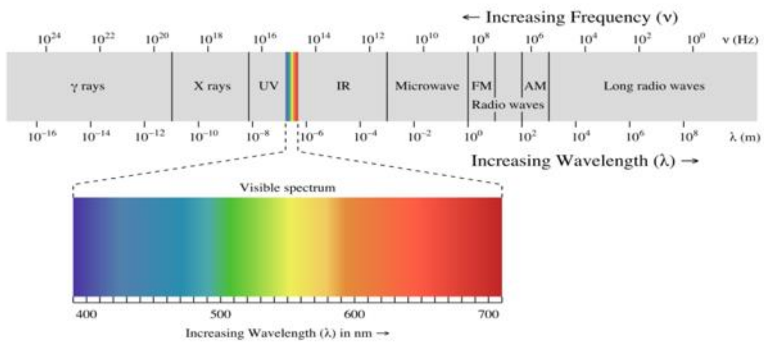
3. The greater the intensity of the light shined on the metal—that is, the more photons that are striking it—the greater the number of electrons emitted.

4. Quantized energy can have only certain allowable values. Non-quantized energy can have any and all possible values.

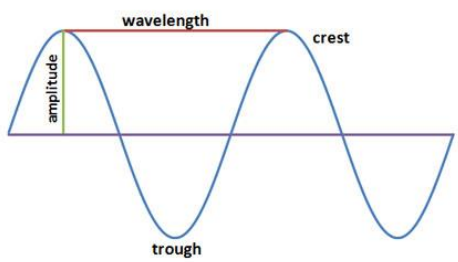
4.4 Illuminating Relationships

Newton studied visible light, and Herschel and Ritter proved the existence of infrared and ultraviolet light. But their work begs a curious question: does the electromagnetic spectrum ever end? If infrared radiation is just beyond red light and ultraviolet radiation is just beyond violet light, is there EM radiation just beyond the infrared and ultraviolet? What about just beyond those? Yes, indeed!

As we can see below from an illustration of the full electromagnetic spectrum, other wavelengths of light produce X-rays and radio waves. The shortest classified wavelengths belong to the gamma rays we studied in the last chapter. Gamma rays are given off by nuclear reactions and can cause serious injury. We generally present the EM spectrum as going from gamma (γ) rays to long radio waves, but there is no end to the spectrum in either direction.[4] There are light waves to the left of gamma rays and to the right of long radio waves just waiting to be characterized, utilized in research, and used in ways to benefit society.



Scientists classify light waves according to how long their **wavelength** is. A wavelength is the distance between corresponding points of two consecutive waves. The scientific symbol for wavelength is the Greek letter lambda, λ. The **amplitude** of a wave is the distance between its baseline and its crest (or one-half the vertical-line distance from crest to trough).

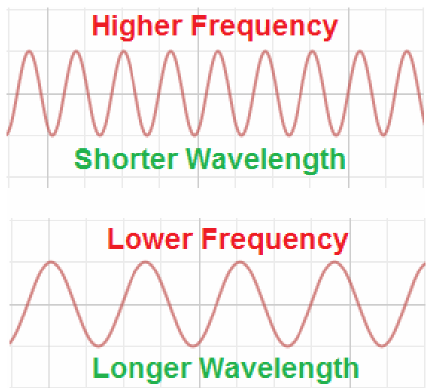


Visible light has wavelengths in the 400–700 nanometer (nm) range. Light near 400 nm has a blue-purple color; light near 700 nm is reddish. Ritter's ultraviolet light has wavelengths a bit shorter than 400 nm, and Herschel's infrared light, wavelengths just a bit longer than 700 nanometers. We can see the results of UV light when we stay outside in the sun too long and get a sunburn, and we perceive infrared light most often as heat. But from the perspective of daily human experience, the main difference between visible light and other wavelengths of the EM spectrum is that we can see the visible band without instruments.

[4] At least, there doesn't seem to be any physical, mathematical, logical, or philosophical *necessity* of its ending in either direction.

In addition to wavelength, a wave has a **frequency**. Frequency is how many waves pass a fixed position in a given amount of time. The symbol used for frequency is the Greek letter ν, nu.[5] If we count how many times a younger sibling interrupts us per hour, we would call that a frequency. If we were fishing off a pier at an oceanfront, we could count how many waves hit the pier every minute, which would be the frequency of the ocean waves at that location. Frequency is defined as the count of something (interruptions, ocean waves, etc.) per unit of time (seconds, minutes, or hours).

We can describe a wave by giving its wavelength *or* by stating its frequency. A wave with a short wavelength will have a high frequency. It's rather logical if we think about it. If there is a short distance between the top of one wave to the top of the next, then the wave will appear to pass a fixed point very frequently.



Conversely, if a wave has a long wavelength—the distance from the top of one wave to the top of the next—the wave will pass a fixed point with a low frequency. When the measure of one physical property goes up as that of another goes down, we call it an **inverse relationship**. Many things have an inverse relationship. For example, the more time we spend shopping, the lighter our bank account becomes! The more time you take to complete your chores, the less time remains for you to enjoy your hobby.

If we wish to express an inverse relationship in a mathematical equation, we write it in one of two ways:

$$x = \frac{k}{y} \qquad \text{or} \qquad xy = k$$

In an inverse relationship, one value will be in the numerator on one side of the equation; here, that's the *x*. The other value will be in the denominator on the other side of the equation; here, that's the *y*. We could also place both values *x* and *y* in the numerator on the same side of the

---

[5] The Greek letter nu looks a lot like the English letter vee, but we should be careful to write it as ν and not as v. The symbol for velocity is v, and the two symbols are easily confused.

equation. In these examples, the *k* represents a numerical **constant**,[6] so don't think of it as a variable per se. We'll see this pattern of inverse relationship frequently in science, so it's important that we learn to recognize it.

Unlike pure mathematicians, scientists are constrained to use math in such a manner that it gives reliable values for real-world situations. When a scientist wants to express the inverse relationship between frequency and wavelength, for example, he writes the equation this way, substituting for the *k* in the models above the physical constant *c*:

$$\upsilon = \frac{c}{\lambda} \quad \text{or} \quad frequency = \frac{speedoflight}{wavelength}$$

From *celeritas*, Latin for "quickness," the *c* constant used in this equation represents the speed of light, or 3×10^8 meters/second (approximately 186,000 miles per second). This value does not change, and it helps to relate two very different physical properties of a wave, its length and frequency. We can observe an inverse relationship by putting different wavelengths into the equation and calculating frequency.[7]

Sidebar: Quick as a Flash

The speed of light is one of the most important constants in physics. But what does that speed actually mean? 3×10^8 meters per second is roughly equivalent to 670 million miles per hour. If you could ride a bicycle at the speed of light (and survive), here's approximately how long it would take you to travel some common distances.

From San Francisco to New York City	2,568 miles	0.014 seconds
From Paris to Beijing	5,109 miles	0.027 seconds
From Nairobi, Kenya, around the world, to Nairobi again	24,901 miles	0.134 seconds
From Earth to the Moon	238,900 miles	1.282 seconds
From Earth to the Sun	92,960,000 miles	About 8 minutes
From the Sun to Pluto	3,670,000,000 miles	Nearly 5 ½ hours

Or think about this. If the sun vanished from existence, it would take us about eight minutes to realize it. But, oh, would we realize it! Alarmingly soon afterward, our planet would grow dark and cold and begin to spin out of control!

[6] Why is the symbol for a constant a *k* and not a *c*? Much of the initial work on modern physics and atomic theory was done in German. The German word for constant is *Konstante*, so the scientific community settled on using *k* for a constant. We will see it used many times in chemistry, mathematics, and physics.
[7] We will discuss how to enter values like 3×10^8 into a calculator in a future chapter. If this is a new concept, please do not be concerned now. The calculations just show an indirect relationship with numbers.

Example

If the wavelength of a wave increases from 4×10^{-8} meter to 7×10^{-8} meters, how will the frequency change?

$$\upsilon = \frac{c}{\lambda}$$

$$\upsilon = \frac{3x10^8\,m/s}{4x10^{-8}m}$$

$\nu = 7.5 \times 10^{15}$ per second

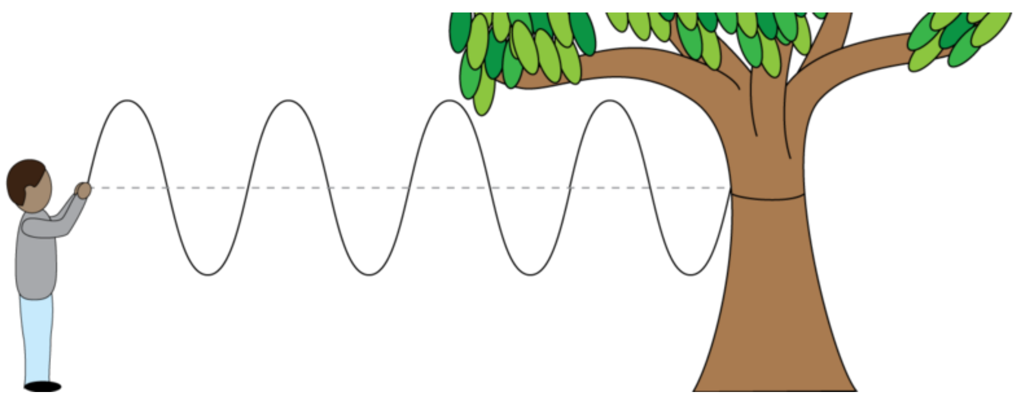
$$\upsilon = \frac{c}{\lambda}$$

$$\upsilon = \frac{3x10^8\,m/s}{7x10^{-8}m}$$

$\nu = 4.3 \times 10^{15}$ per second

When the wavelengths got longer, fewer waves, only 4.3×10^{15}, passed every second. As one value got larger, the other value got smaller. Wavelength and frequency have an inverse relationship.

Inverse relationships don't just exist in the world of light waves. Imagine tying a rope to a tree and shaking the rope up and down. If we shake it up and down rapidly, we can say that the frequency is very high but that the distance between waves is very low. That is an example of the inverse relationship we have been talking about.



It's also hard work. While working hard to move the rope faster and faster, we might conclude that the energy of these waves is very high. Energy and frequency go hand in hand: when energy is high, the frequency is also high. This is a **direct relationship**. When one value of a physical property goes up, another value goes up, too. If we relax and shake the rope less vigorously, we find that we are using less energy. As a result, the frequency at which the waves appear goes down. Again, this is a direct relationship. The amount of food we eat and our weight are in direct relationship. As we eat more, our weight goes up. If you cram more wet laundry into the dryer, it takes longer for them to dry.

Over the last 150 years, scientists have studied waves carefully enough that not only do we know the general relationships that exist between wavelength, frequency, and energy, but we also know the mathematical formulas for these relationships. The formula that converts frequency to energy is

$$E = h\nu$$

Mathematically, we can change frequency (ν) into energy (E) by multiplying it by the constant **h**. This constant is called Planck's constant and is one of the universal constants used by scientists.

SIDEBAR: Intensity vs. Energy

When we say that light has a higher intensity, what do we mean? You might think that a more intense light has more energy, but that's not so. Think back to the photoelectric effect experiment. No matter how *intense* the light got, the same number of electrons were knocked off the metal sheet. This means that *intensifying* light doesn't affect the *energy level* of the light.

So what is intensity? Essentially, light intensity is its brightness. The brighter the light, the more intense it is or the more photons it is delivering. The photoelectric effect experiment demonstrates that the brightness of a light does not change its energy level.

But if the intensity of light doesn't affect its energy level, then what does? The energy level of light changes with the *frequency* of its waves, as shown in the equation $E = h\nu$. Later experiments on the photoelectric effect showed that shining a light with a higher frequency onto the surface of the metal did change the energy of the electrons leaving its surface.

The equation that converts frequency to energy, $E = h\nu$, expresses a direct relationship. If the relationship between two variables is direct, then the two variables will be on opposite sides of the equation and both will be in the numerator. Mathematicians write an equation that shows a direction relationship like this.

$x = ky$ (where *k* is again some constant)

$E = h\nu$

We can easily see that the equation using Planck's constant, h, has the same form as that for a mathematically direct relationship. We can prove that the equation reflects a direct relationship with a simple calculation.

Example

If the frequency of a wave decreases from 8×10^{15} per second to only 2×10^{15} per second, how does the energy of the wave change? The value for Planck's constant, h, is 6.6×10^{-34} joule-seconds[8].

$E = h\nu$	$E = h\nu$
$E = (6.6 \times 10^{-34}$ joule-second$)(8 \times 10^{15}$ seconds$)$	$E = (6.6 \times 10^{-34}$ joule-second$)(2 \times 10^{15}$ seconds$)$
$E = 5.3 \times 10^{-18}$ joules	$E = 1.3 \times 10^{-18}$ joules

When the frequency of the wave dropped from 8×10^{15} appearances per second to only 2×10^{15} appearances per second, the energy also dropped. This is what we would have expected, since energy and frequency have a direct relationship.

Key Point

In an inverse relationship, one quantity gets larger while another quantity gets smaller.

In a direct relationship, when one quantity gets larger, the other quantity gets larger, too.

We have learned about the three ways to describe waves: energy, frequency, and wavelength. We have also looked at what makes direct and inverse relationships. But what does this have to

[8] Panicking yet? Please don't. We will learn more and more about numbers written like 6.6×10^{-34} in future chapters. We use it here just to illustrate the difference between indirect and direct relationships. By the way, a joule is a common unit for measuring energy, though you've probably not run into it yet. You will use it frequently in chemistry and physics.

do with chemistry? Physics and chemistry converge when we talk about light and the nature of the atom. Most modern scientists consider science to be one large discipline, not a collection of isolated and unrelated subjects. Biology and chemistry connect directly when we study the chemical reactions of metabolism or reproduction. Environmental science and chemistry intersect when we look at soil conditions and pollution. Consequently, students who major in chemistry must also be well-versed in biology and physics, and often in other disciplines, such as toxicology, pharmacology, dietetics, or geology.

Review Questions

1. Can you think of quantities that have an inverse relationship?

2. Can you think of quantities that have a direct relationship?

3. Take one of the inverse relationships in the previous problems and build a mathematical equation from it, using any constant.

4. What is the purpose of a constant in a scientific equation?

5. How does changing the wavelength (or color) of light change the energy of the electrons emitted from the surface of a metal?

Answers:

1. Here are a few examples of inverse relationship.
    a. The more hours I shop, the smaller my bank account.
    b. As the temperature goes down, the chance of snow goes up.
    c. The longer I hold my breath, the lower the oxygen content in my bloodstream.

2. Here are a few examples of direct relationship.
    a. The taller I grow, the bigger my shoe size.
    b. The more hours of sunlight, the higher the temperature.
    c. The longer the five-star restaurant is open each day, the more profit it makes.

3. Here is an example of an inverse relationship that has been made into a mathematical equation using the constant q.

$$Time\ Breath\ Is\ Held = \frac{q}{Oxygen\ Content\ in\ Bloodstream}$$

4. The constant relates two (or more) dissimilar physical properties.

5. When we shorten light's wavelength, the distance between the peaks of two waves, we increase the frequency of the wave and therefore its energy. When these more energetic light bundles, or photons, strike the surface of a metal, the increased energy is transferred to the electrons that escape from the surface, and they leave more energetically.

4.5 So Which is It: Wave or Particle?

The logic student looked up from her truth tables to see the physics major approaching from the entrance to the restaurant. She smiled and waved. The physics student was an old friend, but they had lost touch when they started taking different classes.

The physics major pointed at the chair opposite. "May I sit down?"

"Of course! It's been so long since I've seen you."

"I know!" She sat. "What are you working on?"

"Truth tables. For fun!"

"Ah, the life of a math major!"

"Well, what I really appreciate about logic—and math—is that everything is so clear. There are definite answers. Everything is either true or not true; none of that subjective stuff you get in the humanities."

"Well, reality isn't *always* so neat and tidy, not even in the maths and sciences."

"I suppose you have an example in mind?"

"I do, actually," responded the physics major. She paused to order a strawberry milkshake and then continued. "How much do you know about light?"

"Light? It's … all over the place, and we use it all the time. It's blindingly obvious whenever and wherever it's shining. Most of it comes from the sun, even though flames and bulbs can produce it, too. Have I missed something?"

"What you say about light is true, but what *is* light? What's it made of?"

"Well, I'm not really sure. I think I remember that it's a wave of some kind—some of it visible and some of it, like infrared and X-rays, invisible."

"You're right that light behaves like a wave in all sorts of ways. For example, when you shine a light into a pool of water, it refracts, or bends."

"So light is a wave. That seems straightforward enough. I thought you implied there was going to be a problem in here somewhere."

"Well, if light's a wave, can it be *not* a wave, too?"

"Well, no. It can't be both a wave and *not* a wave."

"Are you sure?"

"Well . . . hmm. From the look on your face, I'm a little afraid that I'm falling into a trap here. But logic says no. A thing can't be both *p* and not *p* at the same time, in the same sense."

"Well, here's the problem. There are plenty—a lot—of solid experiments that show light behaving as a wave, yes, but there are also a lot—plenty—that show it behaving like a particle."

"A particle? You mean like tiny little pieces of . . . something?"

"Of energy. Yes. That's precisely what I mean. Many scientists through history have believed that light was a particle—or, to be more accurate, many tiny particles. Isaac Newton argued that light must be made of particles (which he called corpuscles) because light traveled in straight lines. Unless you use another object to force light to change direction (like a prism), it keeps going straight. That's the behavior of particles, not waves, which spread out and oscillate—eh, move up and down in a repeating pattern—as they travel."

"Isaac Newton? Wasn't he responsible for those horrid cookies filled with figs? How much can we really trust him?"

"Very funny—no relation to the cookies (if one can even call them that). This is the fellow who developed calculus, distilled the foundational laws of motion, and also conducted ground-breaking experiments with light. And Newton wasn't the only one who believed that light was made up of particles. Nearly 200 years later, other scientists came to the same conclusion after investigating the photoelectric effect, the strange ability of light to eject electrons from the surface of metal."

"Okay, I think I see where you're going. You want to say that light is both a wave and not a wave, both particle and not a particle. Is that it?"

"You're catching on. What's that principle in logic that says something can't be both one thing and its negation?"

"That's the law of non-contradiction. And it certainly looks like it's been violated here. Light can't be both a wave and a particle."

"Or can it?"

"I'm not sure, but even if it were possible, how would we know?"

"Well, a little-known scientist named Albert Einstein hypothesized that we should treat light as both wave and particle, all at once. In a way, he suggested that scientists set aside the law of non-contradiction and trust what their experiments on light were showing them. And that was Einstein's breakthrough: that light is a particle-like entity that traveled in wave-like ways. His proposal—treating light as if it had a dual nature—became the foundation of quantum mechanics, a field of science that's yielded scads of accurate predictions about the subatomic world and given rise to amazing technologies, such as your smartphone."

"Wow. That does give me something to think about, but I'm not sure we need to give up on logic just because light appears to be both particle and wave."

"I agree. I mean, in most of human experience, logic is an incredible tool that helps us sort out truth from falsehood and see the order in the workings of the world around us. But there *are* places in the world that are still really deep mysteries. Many places, and it's in those places where we find more paradox than neat and tidy answers."

"Hmm. Think we'll ever find out the truth about light?"

"I don't know. Maybe it's one of those things that mankind isn't meant to fully figure out. Or, maybe, another Einstein will catapult our thinking about such things to a whole new level. In the meantime, I'm comfortable with the paradox."

"I suppose I'll have to be, as well, even if it doesn't fit my understanding of the law of non-contradiction. Hey, can I get a ride home?"

"If my car starts, then I'll be glad to. But if it both starts and doesn't start at the same time and in the same sense, then…."

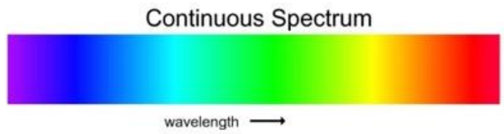
“Clever.”

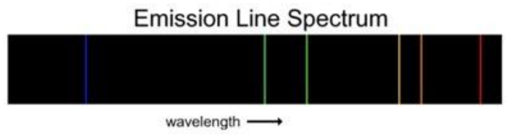
4.6 Show Me the Chemistry

We might think that light has nothing to do with chemistry, but it was light—and its quantum nature—that helped us develop the modern view of the atom. We probably look back at what Einstein proposed in the early 20th century and consider it brilliant. But what happened when he first proposed the concept of wave–particle duality? We might guess that scientists were awed by the cohesive theory and set out to prove it true. In fact, the opposite happened; scientists resisted the notion and tried to disprove Einstein’s idea.

One of the ways they tested Einstein’s notion of wave–particle duality was rather ingenious. Scientists knew that white light from a light bulb or from the sun formed a **continuous spectrum** of colored light when passed through a prism. In other words, the diffraction made visible all of the wavelengths (or energies) of visible light. Since light is just a form of energy, scientists wondered what kind of light a chemical element would give off. The scientists decided to pass an electrical current through a sample of hydrogen gas, making it glow like a street in Las Vegas. They wanted to use the light from the hydrogen to prove that light had only wave properties.

To their surprise, white light and light from electrically excited hydrogen gas gave vastly different results. White light showed every possible wavelength of light in the visible range. Hydrogen gas showed only certain wavelengths in what we call a **line spectrum**.





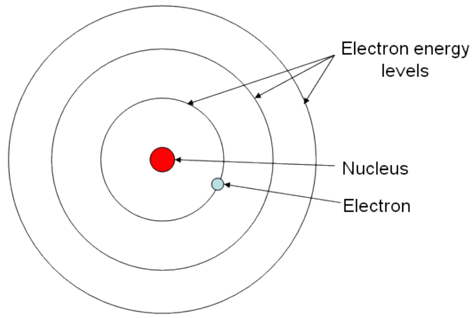
Does this sound a bit familiar? The continuous spectrum, on the one hand, is like the turtle on the ramp: every possible energy level is present. The line spectrum of hydrogen gas, on the other hand, is like the turtle on the steps: only certain energy levels are present. Hydrogen gave a line spectrum that supported Einstein's hypothesis that electrons have only certain allowable energies. The line spectrum also implied that elements like hydrogen had a quantum nature. Far from disproving Einstein's concept of wave–particle duality, the experiment had strengthened it!

Danish scientist Niels Bohr studied the line spectra carefully and developed a model for the atom that refined the one envisioned by Rutherford.

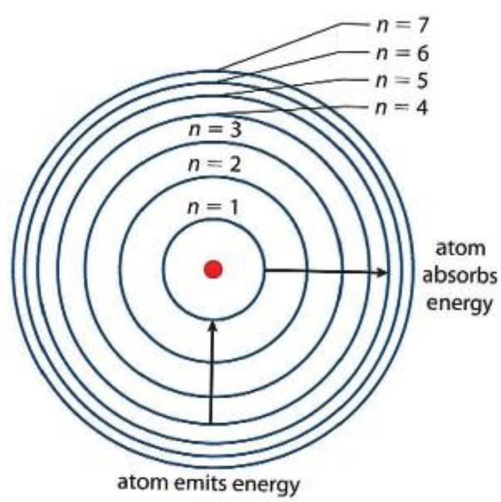
Do We Remember?

Rutherford conducted the gold foil experiment that showed that all of an atom's protons and neutrons are crowded into a tiny nucleus. The electrons are never in the nucleus. They are widely separated in the area surrounding the nucleus.

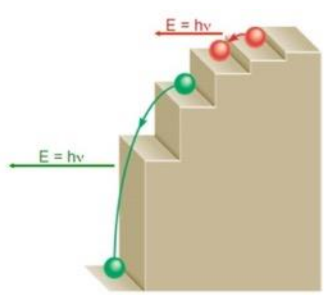
Rutherford had proposed that electrons surround the nucleus of the atom, but placed no restrictions on their location. In his model, electrons could be anywhere outside the nucleus. By contrast, Bohr proposed that because hydrogen gas gave off a line spectrum, indicating that electrons were present only at certain energies, elemental electrons could be located only in certain positions, or orbits, outside the nucleus. These orbits corresponded to the energies displayed in the line spectrum. This 1913 model came to be known as the **Bohr Model** of the atom.



If we slice a spherical atom in half, according to this model, we would see the nucleus in the center and rings, or orbits, where the electrons could be. Each allowable energy level would form a shell, or **principal quantum level**, around the nucleus. Each subsequent shell would have a larger radius than the previous shell, rather like a larger nesting doll conceals a smaller doll inside. Bohr's calculations also showed that the distance between the shells got smaller as the shell got farther from the nucleus.



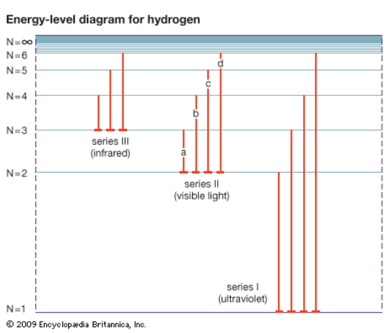
In the Bohr model, an electron may be on this level or that level, but never between two consecutive levels. For example, the red electron can be on the fourth level or the fifth, but not on the 4.5th level (whatever that is).



Bohr assigned each shell a **principal quantum number**, which we refer to with the letter n. The inmost shell, or first level, is n=1. The second level is n=2, and so on. If the electron absorbs energy, it could move from n=1 to n=2 or even higher. The electron *absorbs* energy to move to a higher orbit; it *emits*, or loses, energy to move to a lower orbit.

Does an electron moving from n=4 to n=2 emit the same level of energy as an electron moving from the n=3 to the n=1 level? At first glance, we might assume that since the electron is moving down two energy levels in both cases, the electron will emit the same amount of energy. However, the allowable energy levels, or orbits, are not the same distance apart. It is a smaller distance from n=4 to n=2 than it is from n=3 to n=1. The smaller the distance between two orbitals, the smaller the amount of energy emitted. This is another example of a direct relationship.

Different kinds of energy can excite an electron. Higher-energy ultraviolet light moves an electron a greater distance from the nucleus than lower-energy infrared light. How far can ultraviolet light move an electron? In the range of energies that we classify as UV light, the electron can be excited from the n=1 level to levels 2, 3, 4, 5, or 6. Potentially, we might see five emission lines when the excited electrons relax, or emit energy, to return to the n=1 shell. The weaker infrared energies can move electrons from the n=3 level to levels 4, 5, or 6, a much smaller distance.



Other elements and compounds, like sodium salts or copper salts, give off different emission line spectra. We see the visible light part of their emission spectra when we watch fireworks. Sodium salts give off yellowish colors when the firework explodes, and copper salts give off bluish-green sparkles.

Electrons are not the only particles that have a particle–wave nature. When studying extremely tiny particles, such as protons, electrons, neutrons, and quarks, we must consider that they all have simultaneous wave and particle properties. In other words, we must consider their quantum nature. The nature of quantum reality seems foreign to us, because it is an aspect of the universe we cannot perceive with our immediate senses. Although present all around us, the quantum world must be studied with instruments especially designed to peek into it; it cannot be studied with our eyes. Scientists continue to build instruments to peer into this invisible part of creation and to uncover its mysteries. The results of their experiments continue both to puzzle and to intrigue us . . . and they invite us to ask even more questions about the strangely elegant quantum universe.

Review Questions:

1. Why does light from the sun produce a continuous spectrum?
2. Why does light from electrically excited hydrogen gas give a line spectrum?
3. Would it take more energy to excite an electron from the n=1 to the n=3 level or from the n=2 to the n=4 level?
4. If an electron had been previously excited to the n=6 level, how many possible lines might be seen on a line spectrum as it emits energy?

Answers:

1. Light from the sun is not quantized. All possible wavelengths, and therefore energies, are present. This produces a continuous spectrum.
2. The electrons in hydrogen gas are quantized, so only certain wavelengths, or energies, of light are present. This produces a line spectrum.
3. It takes more energy to move an electron from n=1 to n=3, because the distance is greater than that from n=2 to n=4.
4. An electron that has been excited to the n=6 level could emit energy to return to the 5^{th}, 4^{th}, 3^{rd}, 2^{nd}, and 1^{st} shell. Therefore, we might see five emission lines.

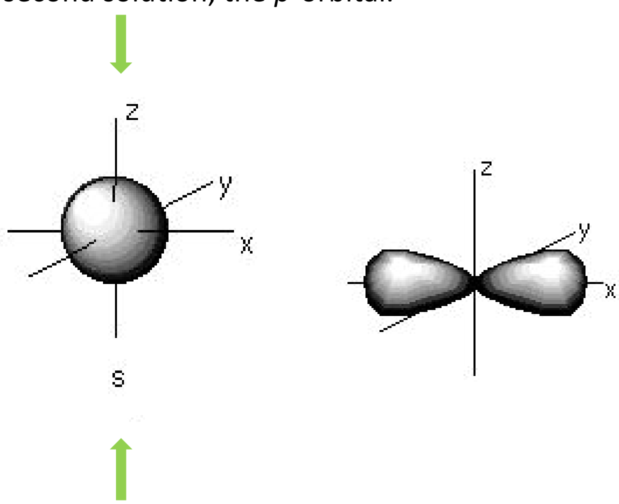
4.7 Bored with Bohr?

Had Bohr proposed the perfect model for the atom? Apparently not. Almost immediately, physicists pointed out a major problem. Bohr’s model had the electron circling the nucleus like a satellite. Critics pointed out that eventually an electron would fall into the nucleus, just as a satellite circling the earth will eventually fall back to earth due to gravity. However, we know that electrons can never be in the nucleus. This cast doubt on Bohr’s model, which also failed to account fully for the wave-like characteristics of electrons.

Erwin Schrödinger /SHRU(R) ding er/ and others continued to refine Bohr’s model and to make mathematical calculations on the nature of the electron. First, the term *orbits* was dropped. The electrons are not orbiting the nucleus in fixed paths like little moons, which is what *orbit* implied. Second, the Austrian physicist put forth in 1926 an even more refined atomic concept, the eponymous **Schrödinger model**, which defines shapes in space that electron wave energies can occupy. These spaces, called **orbitals**, are three-dimensional regions around the nucleus where one is most likely to find electrons. The shapes are the mathematical solutions for the complex equations developed by Schrödinger.

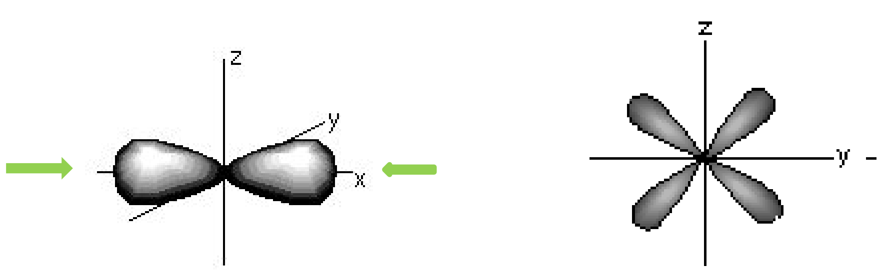
You're familiar with simple mathematical solutions for the equation of a line (when $y = mx + b$) or for the equation of a parabola (when $y = ax^2 + bx + c$). We graph these shapes routinely in algebra. Schrödinger's wave equation is a far more complex formula, but when we graph it, the solutions are distinctive three-dimensional shapes known as *s*-orbitals, *p*-orbitals, *d*-orbitals, and *f*-orbitals. The mathematics behind the shapes is far beyond the scope of this book, but the basic contours of the shapes we can envision and model.

The *s-orbital* is shaped like a beach ball. It is the simplest solution for the wave equation. If we pictured the *s*-orbital sphere being pinched in two directions as indicated with the arrows, we would have the second solution, the *p*-orbital.

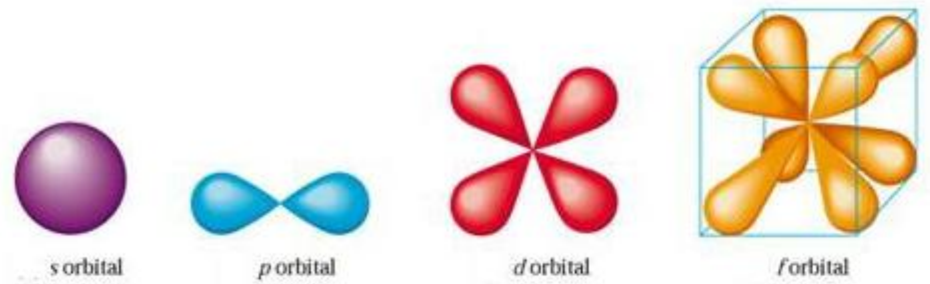


The *p*-orbital has two lobes and a point in the middle, the **node**, where the electron cannot be located. The shape is like a three-dimensional infinity sign (∞) or a peanut.

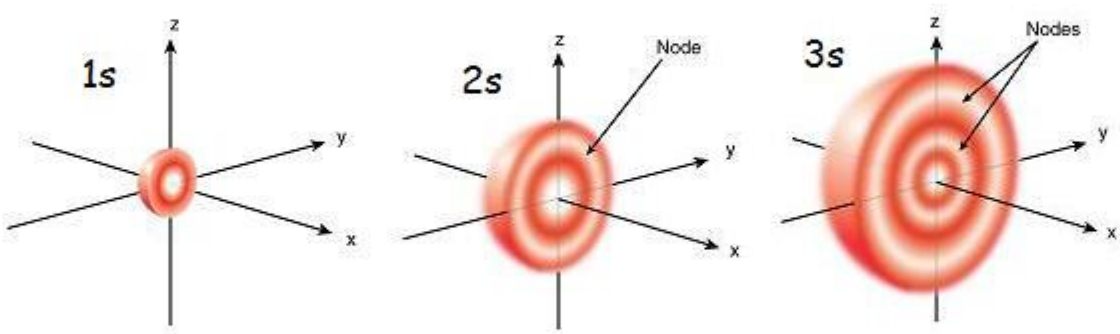
If we pinched the *p*-orbital again, as indicated, we would have the *d*–orbital solution for the wave equation.



The *d*-orbitals are shaped like a four-leaf clover, where each leaf is a puffed-up teardrop. The *f*-orbitals are commonly described as two of the four-leaf clovers attached at the center point, where the electron cannot be located. If we imagined splitting each of the four lobes of the *d*-orbitals, we would have the *f*-orbital shape. The picture below compares these four solutions to the wave equation. The four solutions represent areas around the nucleus of an atom in which electrons are highly likely to be found.



How do these shapes incorporate Bohr's ideas? If we were to cut the three-dimensional, spherical *s*-orbital in half, we would see dark bands that correspond to the energy levels in the Bohr model. The white areas, the **nodes**, are places where the electron is not present. The bands correspond to the steps that the turtle could be on in our cartoon on quantum mechanics.

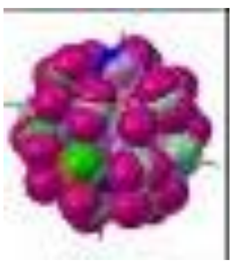


If we made cross-sections of the *p*-, *d*-, or *f*-orbitals, we would see similar bands that correspond to the n=1, n=2, etc., shells. These bands correlate to the periods of the periodic table we saw in Chapter 3.

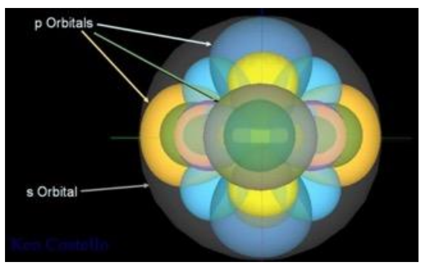
Not every solution to the wave equation, and therefore not every shape of orbital, is available for every row on the periodic table. The first principal quantum level, n=1, has *s*-orbitals only. The second principal quantum level, n=2, has *s*- and *p*-orbitals. This pattern continues as we move farther from the nucleus of the atom. The table below lists the solution shapes for the wave equations at the various principal quantum levels. The orbital shapes in blue are theoretical orbitals for undiscovered elements.

	Type of Orbitals Present
n=1	*s*
n=2	*s, p*
n=3	*s, p, d*
n=4	*s, p, d, f*
n=5	*s, p, d, f, g*
n=6	*s, p, d, f, g, h*
n=7	*s, p, d, f, g, h, i*

We must remember that the orbital shapes are all centered on the same nucleus. They overlap and nest around one another to create a complete atom. When all orbitals are in place, the shape of the atom is remarkably close to a sphere.



or



Scientists are poised to discover in the near future the first element in the eighth principal quantum level. I wonder what new ideas the creation of the 8th period will bring? This 119th element will probably be formed in a linear accelerator by smashing two lighter atoms together, hoping that a new, heavier element 119 forms. Most excitingly for scientists, early calculations predict that element 119 will be stable! We may be able to collect and study this new element and maybe even use it in reactions. Chemists are almost giddy with anticipation because we will get to do a major update of the periodic table at that point, too!

Review Questions

1. Whose model of the atom replaced Bohr's, and what was different about it?
2. What is a node?
3. What orbital shapes will the n=8 principal quantum level have?
4. Which of the orbital shapes in the previous answer will be theoretical shapes only?

Answers:

1. Bohr's model was replaced by Schrödinger's, whose model defined not planet-like *orbits* around the nucleus, but *orbitals*, shapes within an atom's space where electron wave energy may be found.

2. A node is a region of space where electrons are not to be found.

3. n=8 will have *s, p, d, f, g, h, i, j* orbitals.

4. The *g*-, *h*-, *i*-, and *j*-orbitals are theoretical.

Chapter Questions

1. If Herschel had measured the temperature of light just beyond violet, what would he have observed?

2. Explain the significance of Ritter's experiment.

3. What happened when Einstein shined different intensities, or brightnesses, of light on the surface of the metal?

4. How did the results of the photoelectric effect experiment appear to contradict Maxwell's hypothesis that light was a wave?

5. What's the difference between wavelength and amplitude?

6. What's the difference between wavelength and frequency?

7. State whether a relationship is a direct or an indirect relationship.

    a. As the sun goes down, the amount of light available for photosynthesis decreases.
    b. As the number of preschoolers in a room increases, so the number of toys on the floor increases.
    c. As the distance from a train increases, so the decibels of the horn decrease.
    d. As the stock market rises, so the profits from investments rise.
    e. As the pressure of a gas rises, the volume of the gas decreases.

8. Study each scientific equation and state whether the two variables in bold print have a direct or an indirect relationship.

a. P**V** = nR**T**
b. **E**/ν = h
c. **E** = **m**c^2
d. **A**=π$\mathbf{r^2}$
e. 1/(k**A**) = **t**

9. From memory, draw a Bohr model of an atom with five shells. Label the five shells.

10. For each pair, choose the transition that either absorbs or emits the most energy.

a.	n=1 to n=3	or	n=1 to n=2
b.	n=4 to n=3	or	n=4 to n=2
c.	n=1 to n=3	or	n=2 to n=4
d.	n=5 to n=3	or	n=6 to n=4
e.	n=4 to n=1	or	n=5 to n=2
f.	n=5 to n=4	or	n=5 to n=3
g.	n=7 to n=3	or	n=6 to n=2

11. If an electron relaxes from the n=4 level, how many emission lines might we see?

12. An electron in the second energy level absorbs energy. One quantity of energy promotes the electron from the second to the fourth energy level. A different quantity of energy promotes the electron from the second to the seventh energy level. Which quantity of energy comes from infrared and which from ultraviolet light?

13. From memory, draw an *s*-orbital, a p-orbital, and a *d*-orbital.

14. What shapes of orbitals will likely be present if we discover elements with an n=9 shell?

15. Why do we use the term “orbital” rather than “orbit” when describing the energy levels of electrons?

16. What does it mean when we say that energy levels in an atom are *quantized*?

17. What is the evidence that energy in an atom is quantized?

18. According to the Bohr model of the atom, what happens when an electron absorbs energy?

Chapter Answers:

1. Herschel found that infrared light was hotter than red light. He would have found that ultraviolet light was cooler than violet light.

2. Ritter found that ultraviolet light made the decomposition of silver chloride occur faster than violet light did. This showed that light energy existed beyond visible violet light.

3. The energy of the light was transferred to the electrons in the metal and they were ejected from the surface of the metal. Different intensities of light cause different numbers of electrons to be emitted, but they were emitted with the same amount of energy.

4. If light is a wave, then different intensities of light waves should transfer different amounts of energy to the electrons and they should be ejected with different energies. The photoelectric effect experiment showed that all electrons left with the same energy, regardless of the brightness of light shined on them.

5. The wavelength is the distance between the top (or bottom) of one wave to the top (or bottom) of the next wave. The amplitude is the distance from the baseline to the top of the wave, or half the distance from peak to trough.

6. The wavelength is the distance between the top (or bottom) of one wave to the top (or bottom) of the next wave. Frequency is how often the top of a wave passes a fixed point in space.

7. a. direct relationship
   b. direct relationship
   c. indirect relationship
   d. direct relationship
   e. indirect relationship

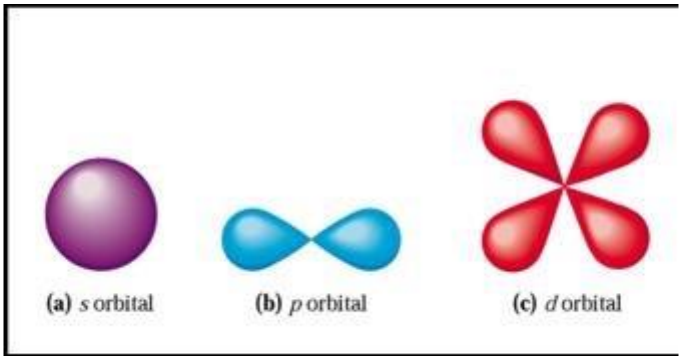
8. a. direct relationship
   b. direct relationship (rearrange to $E=h\nu$ to see why)
   c. direct relationship
   d. direct relationship
   e. indirect relationship (rearrange to 1=k**At** to see why)

9. The picture should have a nucleus at the center and five concentric rings. The rings should get closer together as they get farther from the nucleus. The labels would be n=1, n=2, etc.

10. Determine which transition is the greater distance.
    a. n=1 to n=3
    b. n=4 to n=2
    c. n=1 to n=3
    d. n=5 to n=3
    e. n=4 to n=1
    f. n=5 to n=3
    g. n=6 to n=2

11. The electron in the fourth principal quantum level could emit energy and relax to the third, second, or first level. We could see three lines.

12. Infrared energy is lower energy, so it can move the electron a shorter distance. It moves the electron from the n=2 to the n=4 level. The more energetic ultraviolet light moves the electron from the n=2 to the n=7 level.

13. 

14. *s, p, d, f, g, h, i, j, k*

15. The term “orbital” removes the notion that the electron is a particle traveling in a circle. Eventually, an electron traveling in such a circular “orbit” would fall into the nucleus.

16. Saying that energy levels are quantized means that the energy can be at one level or another, but not in between two levels.

17. The best evidence that energy in an atom is quantized is that atoms produce line spectrums rather than continuous spectrums.

18. When an electron absorbs energy, it is promoted to a higher energy level.

