Chapter 15

Light

doin' the wave

Royal Society, Thomas Young, Henry Briggs, *circa*1822.

Thomas Young, 1773-1829

"Scientific investigations are a sort of warfare carried on in the closet or on the couch against all one's contemporaries and predecessors; I have often gained a signal victory when I have been half asleep, but more frequently have found, upon being thoroughly awake, that the enemy had still the advantage of me, when I thought I had him fast in a corner, and all this you see keeps me alive. "*Letter to Hudson Gurney, 23 Sep 1831*.

By now we're accustomed to treating as Newton infallible ...and indeed, in most of his endeavors, he was bang-on. But then there is the question of the nature of light which was—and in many ways, still is—an enigmatic subject. "Wave or particle?" You've heard that question before, set up as the quintessential example of a choice between opposites. We understand the answer now and "Either-or" doesn't quite work. But in the 18th century the nature of light was indisputably Either-Or! You could side with England or...the *rest* of the world. Newton's ideas of light dominated in his home country in spite of known contradictions, so it wasn't pleasant for the Englishman who overturned him.

15.0.1 Goals of this chapter:

- Understand:
  - goal1
  - goal2.
  - goal3
- Appreciate:
  - goal1
  - goal2.
  - goal3
- Be familiar with:
  - goal1
  - goal2.
  - goal3

15.1 A Little Bit of Young

Everyone we will meet in QS&BB is smart, some are the very definition of genius. But Thomas Young might have given any of them a run for their child-prodigy-money. Born to a huge Quaker family—the oldest of 10 children—Thomas is another in a now disturbingly large list of science-bound children to be raised outside of his immediate family. In this case, his mother's father. He went from school to tutor to school, but learned mostly on his own since he moved faster than any of his teachers. By the time he was 13 years old, he had mastered Greek, Latin, Hebrew, French, and Italian. He'd read Newton's physics and optics. As barely a teenager, he became the tutor to a boy only a year younger from a wealthy family and had access to the family library and read Euclid, history, more Newton, and continued his passion for language with Arabic, Persian, Syriac, and Samarian. Not your normal teenage problem child.

In 1792 he began to study medicine in London and then at Edinburgh, since as a Quaker, he could not study at Oxford or Cambridge and so Scotland was his only choice. It seems he did everything imaginable in Edinburgh except medicine and he followed with two years of study and traveling on the Continent. He actually received his M.D. in Germany and returned to London, renounced Quakerism, joined the Anglican Church and began to study at Cambridge. While he was gone, rules for obtaining membership in the College of Physicians had changed and he would have to spend six years at the university then five more in a hospital. Impatient with this, he quit and began practicing medicine in spite of his British academic shortcomings.

Young's proficiencies were astonishing—and his determination to succeed, otherworldly. For example, when he was a tutor he couldn't ride a horse and repeatedly fell. Yet he became accomplished enough to excel in horse-riding competitions, even executing daredevil stunts.[1] He learned to play the flute, and then became proficient in most musical instruments. While in Germany, he discovered a talent for painting and studied the fine arts. He excelled in dancing and actually choreographed (mathematically) more efficient steps. All the time, he increased his knowledge of mathematics, and always, languages.

While he had been preparing for medical studies in Britain, he studied at St. Bartholomew's Hospital and as a part of his training was instructed to dissect the eye of an ox and in the process developed new discoveries on vision and optics sufficient for publication at the Royal Society at the age of 20. So well-received was this submission, that he was elected a Member of the Royal Society the next year.

In 1797, Young's great-uncle died and left him his London home and sufficient funds for him to be well-off the rest of his life. While practicing medicine in an earnest, but unspectacular fashion, he continued his private studies of, well everything under the sun. He performed measurements on sound and discovered the phenomenon of "beating" when two sounds of different tones (frequencies) interfere with one another.

He also began to speculate on the possible interference effects of light. In 1800 he submitted two papers to the Royal Society, *Sound and Light* and *On the Mechanism of the Eye*. In the latter, he announced the measurement of astigmatism for the first time. (He was near-sighted and can be seen holding his necessary pair of glasses in the portrait above.) In 1802, he delivered a series of lectures at the newly founded Royal Institution[2] covering mechanics, theoretical and practical; hydrostatics, hydrodynamics, acoustics, and optics; and astronomy, the theory of the tides, the properties of matter, cohesion, electricity, and magnetism, the theory of heat and climatology which he eventually published in 1807. It was the most comprehensive account of all of physics ever written.

In 1802, Young published, *The Bakerian Lecture on the Theory of Light and Colours* which described experiments that he'd performed and conclusions that he'd drawn about the nature of light. In what follows below, we'll explore the experiments that Young performed that demonstrated conclusively that light acts like a wave and not like the corpuscles that Isaac Newton had described. Guided by his recognition that sounds interfere with themselves, Young demonstrated that light beams do as well. He found that light can add to itself or cancel itself out and even built a water-tank model as a demonstration for his presentation to the Royal Society.

[1] This, in contrast to Isaac Newton who famously refused to ride in a carriage for fear of it overturning.

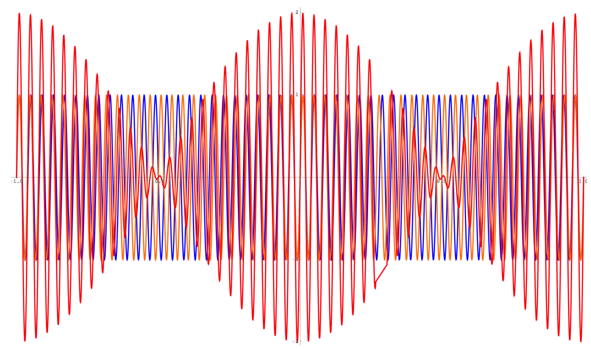

Figure 15.1: Two sounds, one of a frequency of 50 Hz (orange) and the other of 52 Hz (blue) add to produced a louder, "beat" that's the average of the two frequencies. But the amplitude—the intensity of the sound—has its own frequency which oscillates at the difference of the two frequencies, so here, 2 Hz. Sometimes you can hear this on an airplane where engines on two wings might be at two slightly different frequencies and you hear this uh - uh - uh droning.

[2] Founded by the American traitor, Benjamin Thompson, then Count Rumford.

What Young couldn't do was promulgate his theory very far. His reception in Britain was vicious. Notable was the review published (anonymously) by Henry Brougham, a barrister and eventual Lord Chancellor of England and a virulent Newtonian. Some samples of his thoughtful assessment of Young's work are fun. As the Rev. William Henry Milburn wrote in *Harper's New Monthly Magazine* in 1890, "No sooner had Young's 'Memoir on Light' appeared than Brougham rushed to attack him with the fierce savagery of his cattle-stealing, house-burning, marauding forebears. Of all the disgraceful papers to be found in the Edinburgh at this period, I suppose none deserves such odium as those furnished by Brougham on Young."

> As this paper contains nothing which deserves the name, either of experiment or discovery, and as it is in fact destitute of every species of merit, we should have allowed it to pass among the multitude of those articles which must always find admittance into the collections of a Society which is pledged to published two or three volumes every year...We wish to raise our feeble voice against innovations, that can have no other effect than to check the progress of science, and renew all those wild phantoms of the imagination which Bacon and Newton put to flight from her temple... perhaps we might be inclined to pity the misguided pursuits of an ingenious man, who seems to have systematised [sic] into a sort of theory the method of wasting time...We take our leave of this paper, with recommending it to the Doctor to do that which he himself says would be very easy; namely, to invent various experiments upon this subject...we recommend him to employ his winter months in reading the Optics, and some of the plainer parts of the Principia...

Young published a pamphlet of defense but Rev. Milburn noted, "Dr. Young answered the attack of his reviewer in a vigorous, manly, and convincing manner. Only one copy of his pamphlet, however, was sold, and no private means were used to secure its circulation; it produced, therefore, no effect whatsoever in correcting the impressions which had been produced upon the public mind by Brougham's attacks. It was reserved for Arago and Fresnel to become at a much later period...the expositors and interpreters of these memoirs, and to rescue them from the neglect which they had so long and so unjustly experienced from his own countrymen."

Young essentially dropped out of physics research at that point and intensified his interest in languages. The Rosetta Stone is a hieroglyph from the second century, B.C. which was a decree issued in Egypt for King Ptolemy V. It was in three scripts: Ancient Egyptian hieroglyphs, Demotic script, and ancient Greek.

It was brought to Europe by the French in 1801, and on display in the British Museum and Young visited and was inspired. A more pleasant way to spend his time, he attacked the ancient Egyptian written language with all of the tools that he, almost uniquely possessed. The goal was the transliteration of the texts and a formal understanding of the strange, pictorial Egyptian writing. There was a race on to crack the old, old code and it was a Frenchman, Jean-François Champollion who completed the job. But the key to understanding came from Young, who published and corresponded with Champollion who in turn, credited Young for his contributions.


Figure 15.2: rosetta

Young married, but had no children. He continued his role as secretary of the Royal Society. While traveling in Geneva, Switzerland he took suddenly ill and died there in 1829 at the age of 56. He was among the most prolific scientific writers of his or any time. He published significant works in medicine and disease after leaving physics research and yet somehow, was unheralded in his own country, in his own time. He was most proud of the recognition given to him by the Institute of Paris as an elected foreign member in 1827. The French scientist and friend, François Arago noted in his eulogy of Young at the Royal Institute, “The death of Young in his own country attracted but little regard.” Needless to say, Young was right in his criticism of Newton’s particle-formulation of light. It took continental scientists to confirm his ideas and embed them into the story of physics, where Young’s work is celebrated today. Let’s see what he did.

15.2 Newton and Optics


Figure 15.3: newtonfire

Newton’s relationship to optics was mixed, but for a century, this was his most publicly accessible research. His introduction—and quick election— to the British Royal Society was in January of 1672 at the age of 29. It was based on his unique reflecting telescope that he’d given to the Society the year before, a year after he began lecturing on optics. He sent his first written public description of light and color the year he was elected, and drew immediate outrage from Robert Hooke, starting a bitter feud that weirdly continued on Newton’s side even after Hooke’s death.

Newton’s theory of optics was the subject of his first scientific publication in 1674 and also his last substantive book in 1704: his long-overdue *Optiks* was published only after he had stopped doing science and had left Cambridge. His plague-time breakthrough included his discovery that white light (he used sunlight, so not completely white) was a mixture of colors—it was composite, not a primary color. He performed experiments with prisms, “taking apart” a beam of light into color bands and then manipulating them separately and together to demonstrate his premise that the prisms don’t modify light and that the

Figure 15.4: kneller2

Figure 15.5: kneller3

colors could not be further reduced. This was in opposition to the prevailing view (Descartes) that white was an actual color of its own.

Why did he wait so long to publish arguably his first discoveries? This question edges into one of the legendary Newton stories. Remember that his first issuance of the Principia was in 1686 (Book I), continued in 1687 (Books II and III). In addition to the super-human concentration that this effort required, a lot was happening in Newton's life during these years. King Charles II decided that any faculty person at a university that trained Anglican ministers, must likewise be ordained. Newton was prepared to resign but went to London to petition for exception—in hindsight, it's clear that he was beginning to seriously question the Trinity and other Christian beliefs and this would have meant his dismissal. After more than a month in London, the king relented. After the revolution, in 1689 Catholic James II tried to re-Catholicise Cambridge. This was too much for the faculty and he was selected by the them to formally oppose the King...successfully. This unlikely venture into university politics actually led to his election to Parliament that year (the year of the Kneller portrait at the beginning of Chapter **??**). (He served, but is on record as only have spoken one time: to ask that a window be closed.) Newton became a regular in London, befriending a number of intellectuals, including John Locke. He maintained his famous correspondence with Richard Bentely in 1693. Newton was on the top of his game in those years, and then the bottom fell out.

Some time around 1692, there was apparently a fire in Newton's laboratory. Historians argue about this, but Huygens makes reference to it in his notebooks. How the fire started is argued about as well, some say that his alchemical experiments got out of hand—he had large, hot fires burning all the time as he tried to separate and combined various substances trying to solve ancient alchemy problems. So, maybe negligence in the lab? Or Diamond did it: the urban legend is that his beloved dog, Diamond, was so excited at the arrival of a visitor, that he knocked over a candle as depicted in the early 19th century engraving from n 1833 Newton biography (Figure 15.3). This fire is said to have destroyed hundreds of pages of manuscripts, which might have included the first draft of his book on optics.

Then something happened to him. Nobody disputes that he had a second, serious nervous breakdown. He became despondent and dangerously depressed...he would have insomnia for as many as five days in a row, writing deranged letters to colleagues, and terrifying his friends who feared for his emotional state. Huygens' description sums it up:

> "M. Colin, a Scotsman, informed me that eighteen months ago the illustrious geometer, Isaac Newton, had become insane, either in consequence of his too intense application to his studies, or from excessive grief at having lost, by fire, his chymical laboratory and several manuscripts. When he came to this Archbishop of Cambridge, he made some observations which indicated an alienation of mind. He was immediately taken care of by his friends, who confined him to his house and applied remedies, by means of which he had so far recovered his health that he began to understand the 'Principia."'..."I am very glad that I received information of the cure of Mr. Newton, at the same time I had heard of his illness, which doubtless must have been very alarming." The first, is from Huygens' notebooks, the second in correspondence with Leibniz. From *The Life of Sir Isaac Newton*, by Sir David Brewster, 1833.

Whether it was the fire or overwork, nobody knows. There is considerable speculation about the close friendship that Newton had with a young Swiss mathematician, Fatio de Duillier. Their friendship ended abruptly just before his breakdown. He recovered within a year and by some accounts—again, a controversial issue—his personality had changed. Certainly, his life did.

He was offered the position of Warden of the Mint,[3] accepted, and moved to London in 1696. By 1700 he was promoted to Master of the Mint and resigned his Lucasian Chair of Mathematics the next year. He was now a full-time London resident and engaged in the social scene with his live-in niece.[4] He again sat for a portrait by Kneller, Fig. 15.4.

[3] He became Master of the Mint and spent his time catching counterfeiters in London, even donning disguise to go under cover and ruling over multiple hangings.

[4] Catherine Barton was brought to London by her uncle to help him maintain a household. Apparently stunningly beautiful and brilliant herself, she caused men to do silly things. Like when Newton's friend and benefactor, Catherine Barton, Charles Montagu, Lord Halifax left her 5,000 pounds and a furnished London house, "to her as a Token of the sincere Love, Affection, and Esteem I have long had for her Person, and as a small Recompence for the Pleasure and Happiness I have had in her Conversation." She left Voltaire, Swift, and patrons of the Whig drinking club, the Kit-Kat Club, apparently dizzy with her charms. She married a retired soldier and they continued to live with her uncle until his death.

Robert Hooke went on to become the President of the Royal Society, dying in that post in 1703. Newton was elected to follow him and only then did he publish the book on optics which he'd finished years before. It was almost chatty—written in English—and in it he described experiments and laid down his belief in just what light actually is. Both Hooke and Huygens insisted that light was a wave-like phenomenon and Newton—the king of matter and motion—insisted that light was made up of corpuscles: particles, just a more rarefied version of regular matter. Robert Hooke and Newton tried to argue their differences in letters, but in 1680 Newton severed all ties with him.[5] Later he furiously scratched out all mention of Hooke's name from the final edition of *Principia* and even "lost" the official portrait of Hooke that had hung in the President's office. Only in recent years has a single portrait of Hooke been identified.

[5] Newton tried to patch things up, or so it's sometimes thought. He wrote famously to Hooke in 1676, "If I have seen further it is only by standing on the shoulders of giants." Sounds nice, but it's also the case that Robert Hooke was short, emaciated and perhaps physically deformed with a hunched back. Was Newton making fun of him? Anything was possible between those two.

Newton's 30 years in London—a full second life—were eventful. He was knighted by Queen Anne in 1705 and continued to publish editions of *Principia*, *Optics*, as well as other mathematical books. Controversy persisted over who invented calculus first, Newton or Leibniz. In 1712 Newton commissioned a Society panel to investigate the controversy, wrote the report himself, and declared the matter settled.

He remained Master of the Mint and President of the Royal Society until his death in 1727. He was plagued by bladder stones and was unable to eat much but broth by the end. He died in London at the age of 85—pretty good for a premature, tiny baby not expected to survive a day—and was buried in Westminster Abbey in a funeral that was fit for royalty. His monument was unveiled in 1733 and is visited by millions today.

Figure 15.6: newtonwest

Bizarrely, his alchemy and weird biblical prophesy research occupied an enormous and totally secret effort. About the latter two subjects he wrote much more than he did on scientific topics. It was a mess. There were almost 2,000 bound booklets, stacked without order or catalog. They were kept secret by his niece and her husband, and they promulgated the story that Newton was in every respect a committed English Christian. In fact, he had become convinced through his research that Christianity was poisoned in the 4th century with the invention of the Trinity. Economic hardships in the early 20th century led Newton's ancestors to sell his non-scientific writings and we owe much to the early 20th century economist John Maynard Keynes who purchased and cataloged them as a hobby in the 1930s.

The legacy of Isaac Newton is unmatched by any scientist or mathematician. While Albert Einstein overturned much of his mechanics, he had three centuries of scientific culture and sharpened mathematical tools at his disposal when he re-invented physics in our modern sense. Isaac Newton had to invent it all.

15.2.1 Competing Theories of Light

Particles bouncing was Newton's specialty! Reflection of light seemed like a natural example of light-particles recoiling from a flat surface. Likewise, sound bends around corners, but light doesn't. Newton attributed that to light's particles just behaving according to his First law.

But trying to explain other features of light this way required him to do some inventive dancing around obvious stumbling blocks. Diffraction and refraction for example didn't lend themselves easily to a particle explanation. His Model made the prediction that the light particles actually speed up when they passed from a rare medium (like air) into a denser medium (like water). Ultimately, after light was shown to have interference effects that were purely wave-like, the final nail in Newton's light-coffin came in the 19th century when the speed of light in different media was shown to be exactly opposite from what he predicted.

Hooke and Huygens' wave theory of light wasn't without problems. For example, what's waving? If light is a wave, then some medium must be moving like air moves under the influence of sound. Thus was born the idea of the "Luminiferous Ether," this strange all-penetrating substance was thought to be required in order to vibrate in support of light's propagation. The "ether" had to be everywhere, all around us, through everything transparent, and in outer space: after all we see the stars, so it must extend beyond the Earth. This problem hung around for 250 years.

Under everyday circumstances visible light clearly behaves like a wave and therein lies one of the more intriguing detective stories in the history of physics. After some reminders of what a wave is, we'll use these ideas to tell this story, and then use wave parameters over and over in what comes afterwards. Let's follow the story up to the upending of Newton's hold on British interpretation of light.

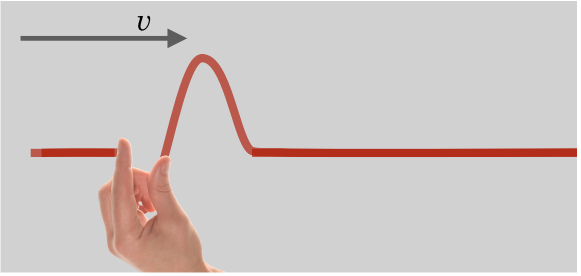

Figure 15.7: A "pluck" of a string transmits the potential energy of the displacement of the particles in the string through the tension and relaxation of the string. The disturbance moves away, while the bits of string stay put.

15.3 Wave Goodbye

Let's think in terms of basics: the obvious features that distinguish particles and waves. It's useful to think of idealized examples: an ideal particle will be one that's infinitesimally small while an idealized wave extends in infinite directions and is perfectly repeating.

So, what is the most characteristic feature of a particle? That's easy: Particles have a "place," a definite location in space—it's "here." And furthermore, when it's here, it's also not simultaneously "there." But a wave is everywhere, all the time. You can't get much more different than that. It sounds almost like a distinction that only Aristotle could make, even if true.

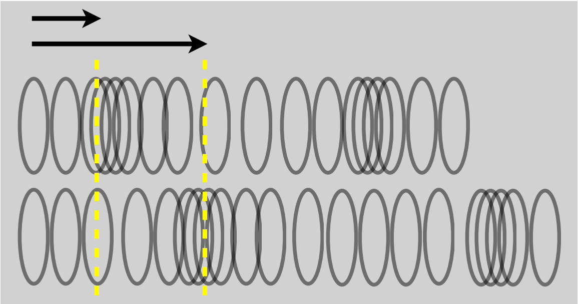

Figure 15.8: This is a longitudinal wave with the disturbance moving along the direction of the "slinky" and in the same direction as the speed of the wave.

But there are also tenuous similarities. Particles carry kinetic energy and transmit it through collisions with other particles. So too a wave is a disturbance that transmits energy. The tremendous destruction of a tsunami is terrible evidence of how energy can be imparted by waves. But the difference here is that the actual constituents of the wave don't themselves translate but they stay put. Figure 15.7 shows a finite disturbance like in a guitar string. If you pluck a stretched string, you'll create a disturbance that will actually move down the length of the string at a predictable speed where it would stop, or reflect and come back. If the string is attached to a bell clapper, it would ring. Obviously, energy and momentum have been transferred from your fingers through the string, sufficient to ring the bell.

Waves transmit energy. *Key Concept 1*

It will be useful to think of waves as simple "sine waves." That's a simplification.[6] It's also useful to contrast two kinds of waves: Longitudinal and Transverse. Longitudinal waves are compressional, like a slinky toy and appear in Nature most readily in the propagation of sound.

When a noise is made the noisemaker vibrates and leaves a momentary compression or rarefaction in the surrounding air—a local high or low density region. This back and forth of high and low densities moves outward as the propagating sound wavefront. Actual molecules of the air don't follow the

[6] We will see later that any such non-repeating shape can actually be built up by a set of infinite sine waves of different wavelengths.

Definition: Longitudinal Wave.
A wave in which the disturbance is along the direction of motion.

Definition: Transverse Wave.
A wave in which the disturbance is perpendicular to the direction of motion.

wave all the way to your ear—local air molecules move and affect adjacent air molecules and that hand-off-disturbance is what propagates. You eventually hear the sound, because that disturbance eventually reaches your ears and bangs on your eardrum like . . . well. . . a drum. Figure 15.8 shows two positions of a compressional disturbance along a spring-like substance.

Transverse waves are different in that the disturbance is not in the direction of the propagation, but perpendicular to it (that's the definition of "transverse"). Water waves are the simplest example. If you toss a stone into a lake, the disturbance is the water going up and down but the wave propagates "outward" from the source in concentric circles. Again, the actual molecules of the water don't move outward with the wave, the water molecules move up and down and affect adjacent water molecules through the tension in the water's surface—rubber ducky just bobs up and down, he doesn't follow the wave. Figure 15.9 shows a typical (infinite) transverse wave.

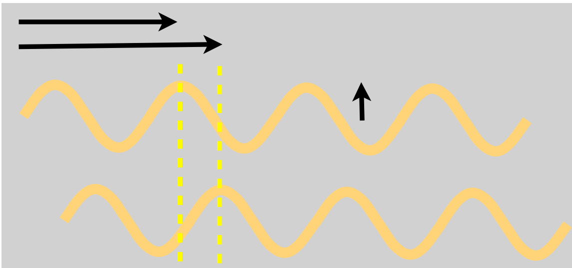

Figure 15.9: This is an example of a transverse wave where the disturbance is up and down, but the propagation of the wave is along the length—perpendicular to the disturbance (hence "transverse"). Notice that each peak (and valley...and every point in between) has moved to the right between the top and bottom snapshots of the wave.

15.3.1 Wave Parameters

We can characterize a moving sine wave with only a few parameters, which are are familiar from everyday life: frequency, wavelength, and amplitude. Notice that a wave is oscillating in space—you see the water wave undulate where the peaks are all in a pattern outward from the disturbance. But also a water wave oscillates in time where each point on the surface of the water is rising or falling in rhythm with all of the other points on the surface. That means we could plot the wave as either a pattern in space or time and the functional description of a wave would contain x and t variables. Figure 15.10 and Fig. 15.11 show these two circumstances with three important features of waves indicated on each.

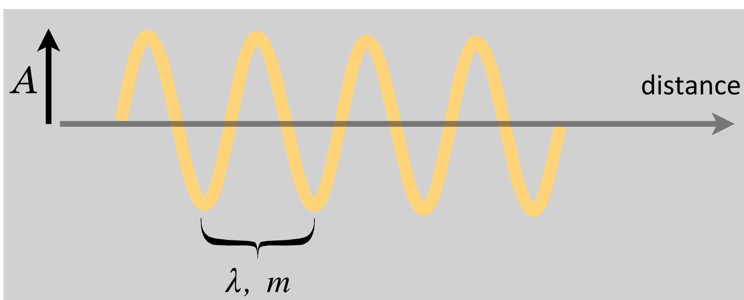

Figure 15.10: As a representation over distance, the disturbance varies with distance in a periodic way and the length of that repeating distance is the "wavelength," λ.

The two most obvious parameters in the space picture are:

- the *wavelength* which is the distance in space units between any two equivalent values of the disturbance along the length of the wave (using the Greek letter, lambda λ) and

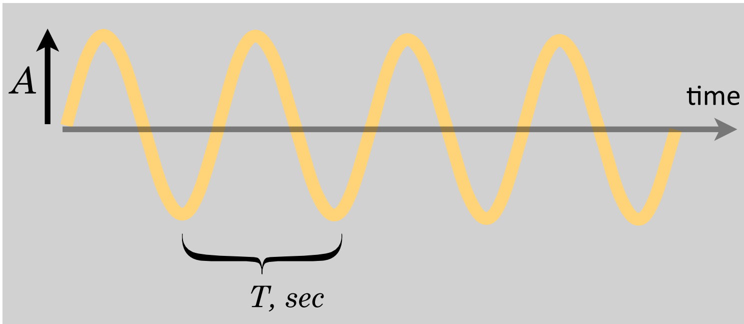

Figure 15.11: As a representation in time, the disturbance varies in time in a periodic way and the duration between points that repeat is the "period," T.

- the *amplitude*, A, the maximum disturbance which can be a length (like the height of water waves) or related to other measurable parameters like the value of pressure or light intensity or other not-so-obvious quantities.

In the time picture there are also two obvious parameters:

- the *period*, usually represented as T—which is the time that it takes for any same value of the amplitude to repeat (which is measured in seconds) and
- the same amplitude as in the space picture!

The most common wave parameter—it's on every radio dial—is the *frequency* which is the rate at which the wave repeats: the number of repetitions per unit time which has the units of s^{-1} or "per second." This is given the name Hertz (Hz), after the great German physicist who first detected electromagnetic waves, Heinrich Hertz (1857-1894). House electrical current in the United States is a sinusoidal shape (alternating current, or "AC") with a frequency of 60 Hz, or 60 cycles per second. I'll use the symbol f for frequency, although it's also commonly represented as the Greek letter ν.[7] Obviously, if the rate that the wave changes is f ("cycles per second")and the time interval between the changes is T ("seconds per cycle"), then:

$$T = 1/f \tag{15.1}$$

The space and time representations of the pictures of waves are connected by the actual speed of the wave (which makes sense since speed connects space and time!). This connection is the important relation,

$$v = \lambda f. \tag{15.2}$$

The speed of a wave depends on the medium, its density, temperature, structure, and so on. But, the speed doesn't depend on the wavelength or the frequency (or the amplitude), so if the frequency goes up for

Definition: wavelength.
The distance in space between peaks of a sinusoidal wave.

Definition: period.
The time difference betwen the peaks of a sinusoidal wave.

Definition: frequency.
The rate at which peaks reappear in a sinusoidal wave. It is the inverse of the Period.

[7] to avoid mistaking ν for velocity's v

Equation: Period of a wave.
$T = 1/f$

Equation: Speed of a wave.
$v = \lambda f$

some wave (like sound) because the speed stays the same, the wavelength goes down. High frequencies mean smaller wavelengths, and visa versa.

Example 15.1

Examples.

Question : What are the wavelengths of: the lowest C on a piano (32.7 Hz); WKAR AM radio radiation (871 kHz on your radio dial)? Assume that the speed of sound in air is 341 m/s and that the speed of light in a vacuum is 3×10^8 m/s.

Solution: We can easily use Eq. 15.2 twice to find these.

$$\lambda = v/f \text{ so:}$$

$$\lambda(\text{low C}) = 341/32.7 = 10.7 \text{ m}$$

$$\lambda(\text{WKAR}) = 3 \times 10^8/871 \times 10^3 = 344.4 \text{ m}$$

15.3.2 Wave Interference: The Smoking Gun

Our idealized particles bounce off of one another—they change their momenta in a collision and are physically unchanged or are broken into pieces. Furthermore, two particles own their own spaces and don't share them. Two particles at the beginning, two particles at the end.

What about waves? They can collide with particles (that's rubber ducky riding up and down in a bathtub wave) or waves can collide with other waves. But when there is a wave-wave collision the result is a *third* wave which is different from its parents. Waves mix themselves in the same space—they interfere with one another, adding and subtracting from the amplitudes of the colliding waves.

Definition: Interference.
Waves interfere and mix their amplitudes positively ("constructive interference') and negatively ("destructive interference").

The top of Fig. 15.12 shows two waves of the same frequency (and wavelength, so the same speed) and the same amplitudes which are added together while they are both "in phase," meaning that their peaks happen at the same times and at the same place in space. Such overlapping waves' displacements would add and the resulting wave would have a peak at twice the value of the originals. So the waves at the beginning are merged into a third wave at the end.

Alternatively should the waves be exactly "out of phase," like in the bottom part of that figure, so that one peaks positively when the other peaks negatively, then the waves would cancel one another out. Certainly this flat-lined "wave" is different from the beginning waves.

Finally, a more realistic aspect of superposition is when interfering waves have slightly different wavelengths or are slightly out of phase with one another. This is the principle behind AM and FM radio (Amplitude Modulation and Frequency Modulation). Then the additions and subtractions can lead to more complicated patterns than total addition or cancellation. The bottom line is that particle collisions and wave collisions are different: the superposition of waves creates a new wave with an entirely different pattern from the originals. Where particles...mostly just bounce.

This feature of "colliding" waves merging with one another is called "Superposition" —just a word for the additive property of combining waves: when two waves collide the points of disturbance (in space and time) of each wave add or subtract with the other. The obvious reference level is to define the sign of a wave's disturbance to be positive if it's above the undisturbed surface (a crest of the wave above the smooth pond) and negative if it's below (a trough). So depending on the relative phase of the two, if both are rising...the superposition will be higher than either one and if one's rising and the other is falling then the difference will be positive or negative depending on the relative values.

This is intuitive and the image can be brought home with a familiar demonstration: When a shallow pan of water is illuminated from below, then wave phenomena can be captured on film. The idea is easy to grasp—Fig. 15.13 is indeed worth 10^3 words! Here a mechanical device just taps on the surface of the water creating outward-going waves that are circles around the tap-tap-tapping of the mechanical finger. The white crests are interspersed with the dark troughs.

When the water trough is now tapped by two, in-phase mechanical taps on the surface. Each tap sends out identical circular waves, but when they meet superposition leads to patterns of enhanced peaks and troughs. Figure 15.14 shows this pattern—the patterned result is like neither of the single-tap sources.

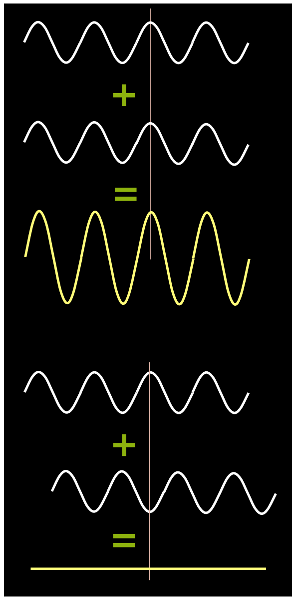

Figure 15.12: In-phase waves add coherently, as in the top pair of waves which sum to the twice-as-high bottom wave. While completely incoherent waves (out of phase) sum to a flat wave...which is no wave at all, as in the bottom set.

Definition: superposition.
The adding and subtracting of individual pieces of a set of waves to produce a composite, resultant wave—the quantitative face of "interference."

Superposition is the principle behind noise-canceling headphones. The electronics in the headphone samples the outside noise and quickly generates nearly identical signals which are exactly out of phase as the canceling contribution.

15.3.3 Forever Young

If you're standing at a concert right behind someone your view of the stage might be totally blocked, but you can still hear just fine. Why is that? Or, a more devious example is when you can stand to the side of a doorway and can't be seen, but you can easily hear what's being said in the next room. While not a nice thing to do, it's an interesting physics example of how waves behave in the presence of obstacles (the concertgoer) or holes (the door.) I'll reserve discussion of obstacles until we are discussing Quantum Mechanics, but let's talk about waves and holes.

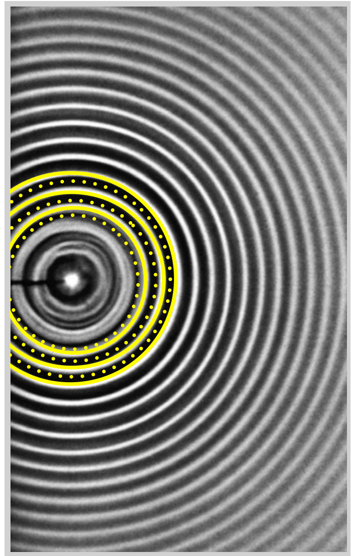

Figure 15.13: A shallow pan of water which is repeatedly tapped with a mechanical “finger” creating a continuously expanding set of circular waves: the light is where the waves crest and the dark, where they have troughs.

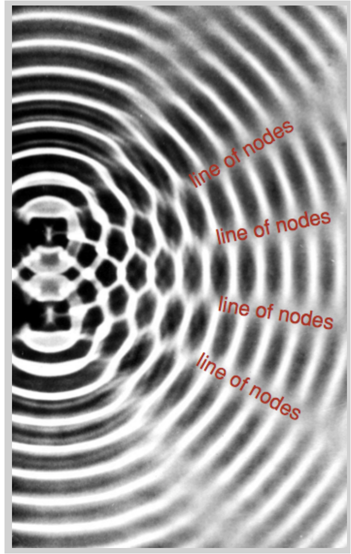

Figure 15.14: The outward spread of the circular waves from two in-time tapping shows radial regions of troughs—called nodes—where there is clear evidence of destructive interference.

When a wave encounters a hole it squirts through but what emerges on the other side depends on the size of the hole *relative to the wavelength of the wave*. If that hole is of comparable size to the wavelength, then the light that passes through does not perfectly show the shape of the hole, but it's fuzzy around the edges. (Likewise, if a wave is blocked by an obstruction which is of a size comparable to the wavelength of the wave, then the shadow that results is not a sharp edge, but again, fuzzy.) The fuzziness in each case is the phenomenon of *diffraction* in which occurs in all wave-solid interactions. That you can hear around a corner is a result of the fact that wavelengths for many audible sounds are comparable to the width of a door opening. If the sound is a very high-pitched one, so it has a very small wavelength (right, high pitch means large frequency, so a small wavelength), it will go right through and not even "see" the door, and would not be heard off to the side. (The opposite thing is true of a person standing in front of you at a concert. The wavelengths of the sound are much larger than the person's width, and so they essentially are not disturbed by the person and you hear just fine.) How is that?

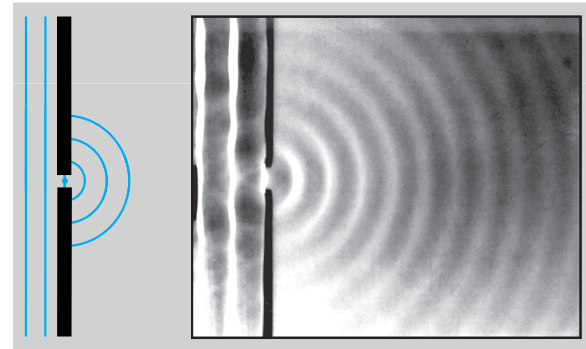

Figure 15.15: A drawing and a photograph of a plane wave incident on a slit whose width is comparable to the wavelength.

Definition: Diffraction.
Waves bend around obstructions and spread out when passing through gaps in barriers.

There is a sophisticated way to show this, but we still use a picture that Christian Huygens intuited in 1690 in his amazing *Treatise on Light*. It's called to this day, the Huygens Construction and it goes like this.

Let's call a "wavefront" just what you expect: the leading edge of some wave that could be nearly spherical (like from an incandescent light bulb), cylindrical (like from a fluorescent light bulb), or even a plane wave (like ocean waves on a shore, or a spherical wave that is a long way from the source). What Huygens found was that he could reproduce various phenomena (that Newton tended to ignore or badly explain) by presuming that every point on a wavefront is itself a tiny little source of a circular (if two dimensions) or spherical (if three) waves—a "wavelet" if you will. Notice that he's essentially using a Calculus-like thinking here: he's imagining these little sources infinitesimally close to one another along a real wavefront...and then he's adding up the contributions from each wavelet. In many places between two of these little imaginary, adjacent wavelets, they would cancel. But they would add coherently like at the top of Fig. 15.12, at one place: parallel to the original wavefront. If there were an infinite number of them, those summed new wavefronts would match the shape of the original and create a new one. Then that would create still yet another set and so on. Figure 15.16 is a diagram from his book that demonstrates this idea.

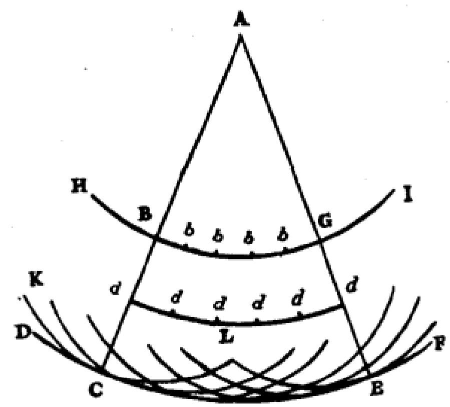

Figure 15.16: words

So in this way of thinking, when even a plane wave impinges on a hole, or in the case of a shallow water trough, a slit, is that across the gap are a string of an infinite, little Huygen wavelets each propagating circularly from the slit, and again creating new wavefronts as it goes along. If the slit is very tiny, then we can imagine that there's only one wavelet at the gap. In fact it would look exactly like the tapping picture in Fig. 15.13: Figure 15.15 shows an approximation to this situation. From the left a plane wave is incident

Definition: plane wave.
A wave that is linear in its extent. An ocean wave is a good example of a near-plane wave.

on a flat wall in which there is a small slit. The width of the slit is about the size of the wavelength and the result is almost exactly like the single tap.

Diffraction occurs when λ and the size of a gap or obstacle are comparable. *Key Concept 2*

Now we know why you can hear around a door. Notice how the wavefronts come "back around" and hit the wall on the other side of the plane wave. If that's you hiding just below the slit on the right hand side, if those bending waves are sound, you'll hear them. For example, Middle C is a frequency of about 261 Hz and since the speed of sound is around 330 m/s, then the wavelength of a Middle C tone is

$$\lambda = v/f$$
$$\lambda = \frac{330 \text{ m/s}}{261 \text{ cycles/s}} \sim 1.3 \text{ m/cycle}$$

and a regular sized door is about that same dimension, so "regular" sounds will bend around doors.[8] Suppose that the door is very much wider than the wavelength? Seen from the other side, the width of the wave coming through the slit almost perfectly matches the width of the door. But at the edges there is still curving...the fuzziness of edge-diffraction shown in Fig. 15.17. The projection of the summed intensities of the water waves are shown on the right drawing. Notice that there is a broad peak directly behind the slit, and then a minimum...and then another peak, and minimum...and so on. The successive peaks and valleys of wave interference is clearly shown in both the photograph and the summed intensities.[9]

Armed with these ideas it's time for Thomas Young to knock Newton from his corpuscular pedestal. As we now know, paying for his place in history, by discovering that indeed, no good deed goes unpunished.

[8] Wavelengths and frequencies are shown in Table 15.1 for relatively common wave phenomena.

[9] Spoiler alert: I hope it would not spoil the story to remind you that visible light waves are a much higher frequency and shorter wavelength than sound waves. A door is much wider (meters) than visible light (hundreds of nano-meters). So, a plane light wave goes marching right through an open door illuminating the room beyond casting a rectangular light area that matches the width of the door. The amount of diffraction around the edges is minuscule: so you can't *see* around the open door like you can *hear* around an open door.

Young's Double Slit Experiment

Suppose you're at a traveling carnival where you throw balls at a hole. Let's pretend that at this *physics* carnival such games include measurements: in this case a brave guy on the other side of the hole patiently noting where each ball hits after it goes through the hole. If the balls are smaller than the hole's diameter

Table 15.1: Wavelengths and frequencies for characteristic wave phenomena. The speed of light in a vacuum is assumed to be 3.0×10^8 m/s and the speed of sound in dry air at 20° C is 341 m/s.

Source	frequency	Wavelength (m)	Medium	Comments
middle C	261 Hz	131.3 cm	air 20° C	at freezing, $\lambda = 126.7$ cm
D above middle C	293.7 Hz	1.16	air 20° C	
C sharp	276.6 Hz	1.2	air 20° C	
lowest audible	20 Hz	17	air 20° C	
highest audible	20,000 Hz	1.7 cm	air 20° C	
lowest C on piano	32.7 Hz	10.4	air 20° C	
color red	0.46×10^{15} Hz	650 nm	vacuum	
Infrared light	3×10^{14} Hz	1 micron	vacuum	
commercial microwave	2.45 GHz	12.2 cm	vacuum	
WKAR AM radio	871 kHz	344.8	vacuum	
WKAR FM radio	90.5 MHz	3.3	vacuum	
US House current	60 Hz	5	vacuum	
ATT GSM LTE cellular	1,900 MHz	15.8 cm	vacuum	
Cosmic microwave background	160.2 GHz	1.87 mm	vacuum	

then every one that passes through would land at about—but not exactly—at the same spot. You might not be surprised if the distribution of the frequency of where the balls hit looked like that of Fig. 15.18.

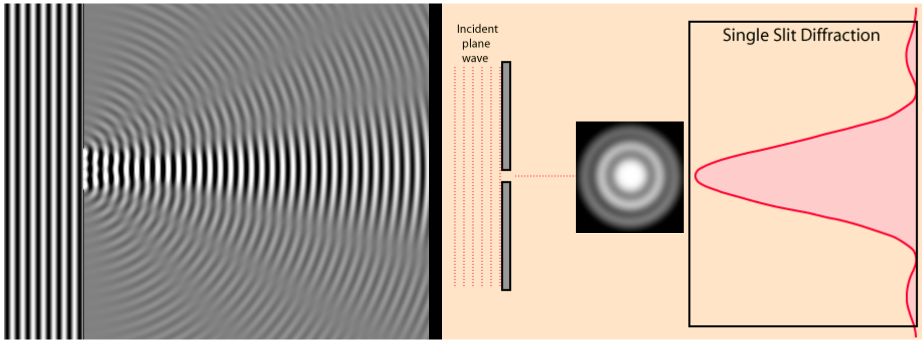

Figure 15.17: With the slit a few multiples of a wavelength, the Huygens Construction starts to produce plane-like wavefronts in the center and still diffractive alternating constructive and destructive interference at the edges.

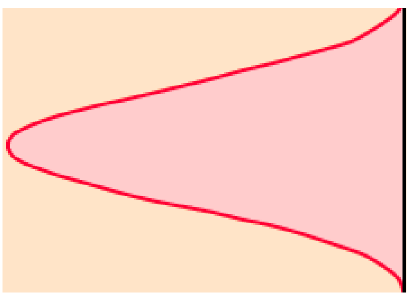

Figure 15.18: The distribution of our balls thrown randomly at a hole. Most of them land at the place where the center of the hole is, while fewer land on either side of that point.

Now suppose that the carny worker at that game suddenly opened a second hole right next to the first. If you're randomly—uniformly—throwing balls at the area where the holes are, you'd see fewer balls go through the original hole, but you'd expect to see that the balls were equally distributed into two piles, side by side, each one of which looked like that of Fig. 15.18.

Suppose however the distribution of balls directly behind the original hole became zero when the second was opened! You'd want your money back! Game rigged! Adding another hole can't make the balls disappear behind the first one.

This turns out to be precisely the behavior that you expect from waves and it's what Dr. Young showed to his hostile audience.

If our carnival is not about balls, but about waves, then the two-hole game is mimicked by just a two-slit water trough. Figure 15.19 shows exactly this circumstance.

Refer back to Fig. 15.17. I've superimposed that curve on top of the two slit result directly to the right of the top slit in Fig. 15.19. When only the top slit is open, there's light at that peak. But when the lower slit is opened in addition, that spot goes dark...no light. By opening a *second* slit...light disappeared at the position where it was brightest from the top slit alone! Adding a hole made light go away! *Only waves can do this* by our new appreciation of superposition. There is no way to arrange for particles to disappear when a second hole opens, like at the rigged carnival.

Definition: Double Slit Experiment.
When plane waves are incident on a barrier with two slits which are comparable in width to the wavelength, then a distinctive interference pattern results.

This is what Mr. Young demonstrated to his British scientific colleagues. He managed to so precisely make slits narrow and a beam of light so intense, that he make the two slit result manifest for all to see. He opened the second slit and the place where the first slit showed light, it now was dark. Now sometimes true believers in something cannot handle the truth and the British were so confident in the unques-

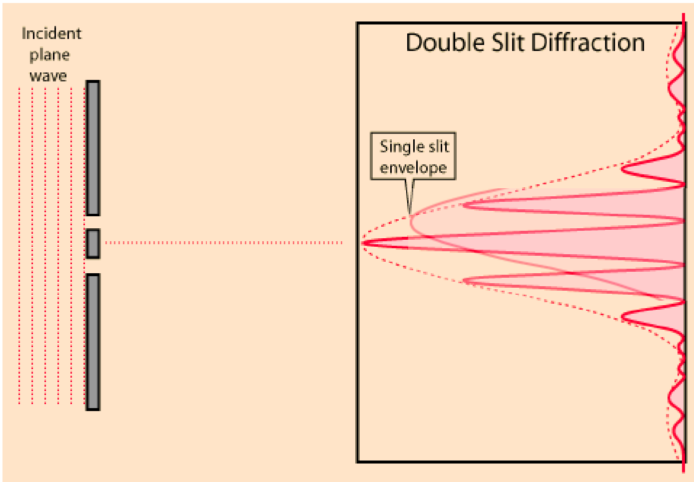

Figure 15.19: Now a second slit has been opened and two unexpected things happen as described in the text.

tioned truth of whatever Isaac Newton said, that in the reaction of Mr. Brougham was to be sarcastically dismissive.

But, the damage to the corpuscular theory had been done. Later, the French engineer Augustin-Jean Fresnel (1788-1827) proposed a model for light that explained the phenomenon of polarization. When passed through some crystals, including coatings on modern sunglasses, the glare of light is greatly reduced. Fresnel explained this by working out a Model (largely while in prison after Napoleon briefly returned to power) of light as transverse waves, which could slip through crystals in some orientations, and be blocked by others. Frensel's story is a little unusual. He entered a competition—mathematicians were always creating and entering solve-this-problem-win-a-prize competitions—and his model predicted a very unusual result, which was disputed by the judges. The experiment was done and confirmed Fresnel's prediction, but the phenomenon became called "Poisson's Spot." You see, Simeon Poisson was one of the judges who ridiculed the prediction and then published out the full solution. Doesn't seem fair, does it?

"Double-slit interference" was the definitive confirmation of light as a wave. *Key Observation 1*

So, at the beginning of the 19th century the study of light had taken a new direction: optical experiments demonstrated that it was a wave-like phenomenon and the metaphor of the day was that the universe was suffused with the ether, the medium which undulated with its passage.