7. Waves

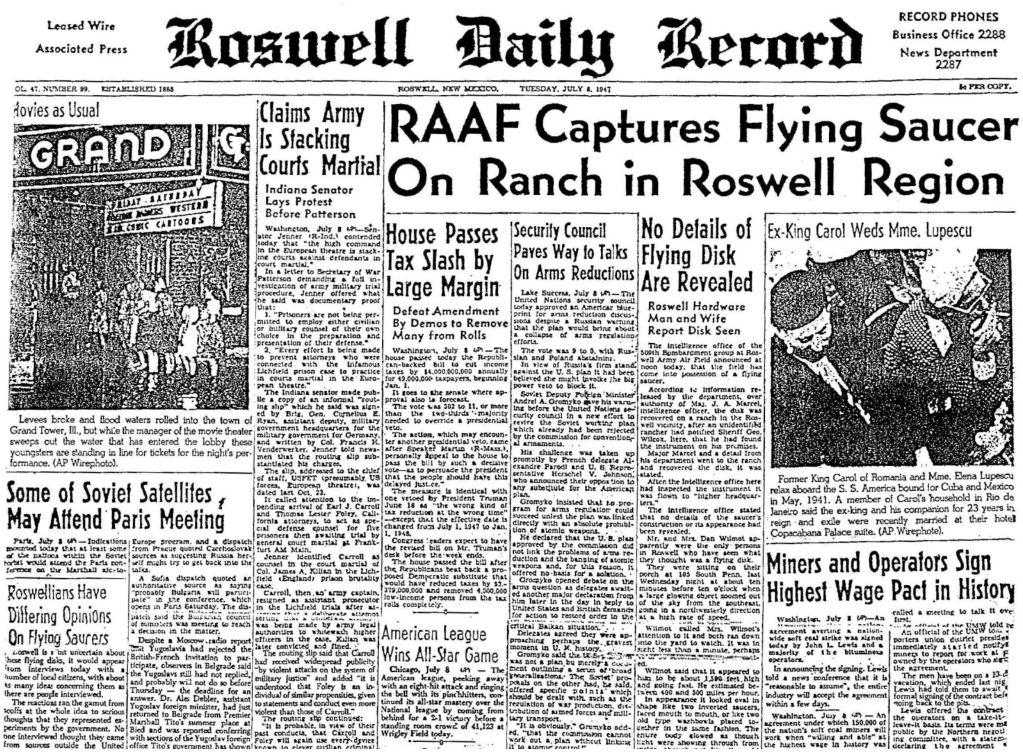
including UFOs, earthquakes, and music

Two strange but true stories

The following two anecdotes, *Flying Saucers* and *Rescuing Pilots*, are actually closely related, as you will see later in this chapter. They both will lead us into the physics of waves.

Flying saucers crash near Roswell, New Mexico

In 1947, devices that the U.S. government called "flying disks" crashed in the desert of New Mexico. The debris was collected by a team from the nearby Roswell Army Air Base, which was one of the most highly classified locations in the United States. The government put out a press release announcing that flying disks had crashed, and the story made headlines in the respected local newspaper, The Roswell Daily Record. Take a moment to look at the headlines for July 8, 1947:



Leased Wire
Associated Press

Roswell Daily Record

RECORD PHONES
Business Office 2288
News Department 2287

OL. 47. NUMBER 99. ESTABLISHED 1888 — ROSWELL, NEW MEXICO, TUESDAY, JULY 8, 1947 — 5c PER COPY.

RAAF Captures Flying Saucer On Ranch in Roswell Region

Movies as Usual

Levees broke and flood waters rolled into the town of Grand Tower, Ill., but while the manager of the movie theater sweeps out the water that has entered the lobby these youngsters are standing in line for tickets for the night's performance. (AP Wirephoto).

Claims Army Is Stacking Courts Martial

Indiana Senator Lays Protest Before Patterson

Washington, July 8 (AP)—Senator Jenner (R-Ind.) contended today that "the high command in the European theatre is stacking courts against defendants in court martial."

In a letter to Secretary of War Patterson demanding a full investigation of army military trial procedure, Jenner offered what he said was documentary proof that:

1. "Prisoners are not being permitted to employ either civilian or military counsel of their own choice in the preparation and presentation of their defense."

2. "Every effort is being made to prevent attorneys who were connected with the infamous Lichfield prison case to practice in courts martial in the European theatre."

The Indiana senator made public a copy of an informal "routing slip" which he said was signed by Brig. Gen. Cornelius E. Ryan, assistant deputy, military government headquarters for the military government for Germany, and written by Col. Francis H. Venderwerker. Jenner told newsmen that the routing slip substantiated his charges.

The slip, addressed to the chief of staff, USFET (presumably US forces, European theatre), was dated last Oct. 23.

It called attention to the impending arrival of Earl J. Carroll and Thomas Lester Foley, California attorneys, to act as special defense counsel for five prisoners then awaiting trial by general court martial at Frankfurt AM Main.

Jenner identified Carroll as counsel in the court martial of Col. James A. Kilian in the Lichfield (England) prison brutality case.

Carroll, then an army captain, resigned as assistant prosecutor in the Lichfield trials after asserting that a deliberate attempt was being made by army legal authorities to whitewash higher officers in the case. Kilian was later convicted and fined.

The routing slip said that Carroll had received widespread publicity "by violent attacks on the system of military justice" and added "it is understood that Foley is an individual of similar propensities, given to statements and conduct even more violent than those of Carroll."

The routing slip continued:

"It is probable, in view of their past conducts, that Carroll and Foley will again use every device known to clever civilian criminal

House Passes Tax Slash by Large Margin

Defeat Amendment By Demos to Remove Many from Rolls

Washington, July 8 (AP)—The house passed today the Republican-backed bill to cut income taxes by $4,000,000,000 annually for 49,000,000 taxpayers, beginning Jan. 1.

It goes to the senate where approval also is forecast.

The vote was 302 to 11, or more than the two-thirds majority needed to override a presidential veto.

The action, which may encounter another presidential veto, came after Speaker Martin (R-Mass.), personally appeal to the house to pass the bill by such a decisive vote—as to persuade the president that the people should have this delayed justice."

The measure is identical with one vetoed by President Truman June 16 as "the wrong kind of tax reduction at the wrong time" —except that the effective date is changed from July 1, 1947 to Jan. 1, 1948.

Congress leaders expect to have the revised bill on Mr. Truman's desk before the week ends.

The house passed the bill after the Republicans beat back a proposed Democratic substitute that would have reduced taxes by $3,379,000,000 and removed 4,000,000 low-income persons from the tax rolls completely.

American League Wins All-Star Game

Chicago, July 8 (AP) — The American league, pecking away with an eight-hit attack and ringing the bell with its pinchhitters, continued its all-star mastery over the National league by coming from behind for a 2-1 victory before a standing room crowd of 41,123 at Wrigley Field today.

Security Council Paves Way to Talks On Arms Reductions

Lake Success, July 8 (AP)—The United Nations security council today approved an American blueprint for arms reduction discussions despite a Russian warning that the plan would bring about a collapse of arms regulation efforts.

The vote was 9 to 0, with Russian and Poland abstaining.

In view of Russia's firm stand against the U. S. plan it had been believed she might invoke the big power veto to block it.

Soviet Deputy Foreign Minister Andrei A. Gromyko gave his warning before the United Nations security council in a new effort to revive the Soviet working plan which already had been rejected by the commission for conventional armaments.

His challenge was taken up promptly by French delegate Alexandre Parodi and U. S. Representative Herschel V. Johnson, who announced their opposition to any substitute for the American plan.

Gromyko insisted that no program for arms regulation could succeed unless the plan was linked directly with an absolute prohibition of atomic weapons.

He declared that the U. S. plan approved by the commission did not link the problems of arms reduction and the banning of atomic weapons and, for this reason, it offered no basis for a solution.

Gromyko opened debate on the arms question as delegates awaited another major declaration from him later in the day in reply to United States and British demands for action to restore order in the critical Balkan situation.

Delegates agreed they were approaching perhaps the gravest moment in U. N. history.

Gromyko said the U. S. ... was not a plan but merely a document outlining a series of broad generalisations. The Soviet proposals on the other had, he said, offered specific points which should be dealt with, such as the regulation of war production, distribution of armed forces and military transport.

"It is obviously," Gromyko added, "that the commission cannot

No Details of Flying Disk Are Revealed

Roswell Hardware Man and Wife Report Disk Seen

The intelligence office of the 509th Bombardment group at Roswell Army Air Field announced at noon today, that the field has come into possession of a flying saucer.

According to information released by the department, over authority of Maj. J. A. Marcel, intelligence officer, the disk was recovered on a ranch in the Roswell vicinity, after an unidentified rancher had notified Sheriff Geo. Wilcox, here, that he had found the instrument on his premises.

Major Marcel and a detail from his department went to the ranch and recovered the disk, it was stated.

After the intelligence office here had inspected the instrument it was flown to "higher headquarters."

The intelligence office stated that no details of the saucer's construction or its appearance had been revealed.

Mr. and Mrs. Dan Wilmot apparently were the only persons in Roswell who have seen what they thought was a flying disk.

They were sitting on their porch at 105 South Penn. last Wednesday night at about ten minutes before ten o'clock when a large glowing object zoomed out of the sky from the southeast, going in a northwesterly direction at a high rate of speed.

Wilmot called Mrs. Wilmot's attention to it and both ran down into the yard to watch. It was in sight less than a minute, perhaps ...ed.

Wilmot said that it appeared to him to be about 1,500 feet high and going fast. He estimated between 400 and 500 miles per hour.

In appearance it looked oval in shape like two inverted saucers, faced mouth to mouth, or like two old type washbowls placed together in the same fashion. The

Ex-King Carol Weds Mme. Lupescu

Former King Carol of Romania and Mme. Elena Lupescu relax aboard the S. S. America bound for Cuba and Mexico in May, 1941. A member of Carol's household in Rio de Janeiro said the ex-king and his companion for 23 years in reign and exile were recently married at their hotel Copacabana Palace suite. (AP Wirephoto).

Miners and Operators Sign Highest Wage Pact in History

Washington, July 8 (AP)—An ... agreement averting a nationwide soft coal strike was signed today by John L. Lewis and a majority of the bituminous operators.

In announcing the signing, Lewis told a news conference that it is "reasonable to assume", the entire industry will accept the agreement within a few days.

Washington, July 8 (AP) — An agreement under which 150,000 of the nation's soft coal miners will

called a meeting to talk it over first.

An official of the UMW told reporters union district presidents immediately started notifying miners to report for work at ... owned by the operators who signed the agreement.

The men have been on a 10-day vacation, which ended last night. Lewis had told them to await formal signing of the contract before going back to the pits.

Lewis offered the contract to the operators on a take-it-or-leave-it basis. Its terms were made public by the Northern negoti...

Some of Soviet Satellites May Attend Paris Meeting

Paris, July 8 (AP)—Indications mounted today that at least some of the nations within the Soviet orbit would attend the Paris conference on the Marshall aid-to-Europe program, and a dispatch from Prague quoted Czechoslovak sources as suggesting Russia herself might try to get back into the talks.

A Sofia dispatch quoted an authoritative source as saying "probably Bulgaria will participate" in the conference, which opens in Paris Saturday. The dispatch said the Bulgarian council of ministers was meeting to reach a decision in the matter.

Despite a Moscow radio report that Yugoslavia had rejected the British-French invitation to participate, observers in Belgrade said the Yugoslavs still had not replied, and probably will not do so before Thursday — the deadline for an answer. Dr. Ales Debler, assistant Yugoslav foreign minister, had just returned to Belgrade from Premier Marshall Tito's summer place at Bied and was reported conferring with sections of the Yugoslav foreign office Tito's government has shown

Roswellians Have Differing Opinions On Flying Saucers

Roswell is a bit uncertain about these flying disks, it would appear from interviews today with a number of local citizens, with about as many ideas concerning them as there are people interviewed.

The reactions ran the gamut from scoffs at the whole idea to serious thoughts that they represented experiments by the government. No one interviewed thought they came from sources outside the United

Serious newspaper headlines from the respected Roswell Daily Record,
RAAF stands for "Roswell Army Air Force".

The next day, the U.S. government retracted the press release, and said their original announcement was mistaken. There were no flying disks, they claimed. It was only a weather balloon that had crashed. Anybody who had seen the debris knew it wasn't a weather balloon. It was far too large, and it appeared to be made from some exotic materials. In fact, the object that crashed was *not* a weather balloon. The government was lying, in order to protect a highly classified program. And most people could tell that the government was lying.

The story I have just related sounds like a fantasy story from a supermarket tabloid--or maybe like the ravings of an anti-government nut. But I assure you, everything I said is true. The story of the events of Roswell, New Mexico is fascinating, and not widely known, since many of the facts were classified until recently. In this chapter I'll fill in the details so that the Roswell story makes sense.

Incidentally, if you are unfamiliar with the name Roswell, that means you have not watched the TV program "The X Files" or read any of the other voluminous literature about flying saucers and UFOs. Try doing an Internet search on Roswell in 1947 and see what you find. Be prepared to be astonished.

Now for the second anecdote.

Rescuing Pilots in World War II

The true story of the flying disks began with an ingenious invention made by the physicist Maurice Ewing near the end of World War II. His invention involved small objects called "**sofar**" spheres that could be placed in the emergency kits of pilots flying over the Pacific Ocean. If a pilot was shot down, but he managed to inflate and get on to a life raft, then he was instructed to take one of these spheres and drop it into the water. If he wasn't rescued within 24 hours, then he should drop another.

What was in these miraculous spheres? If the enemy had captured one and opened it up, they would have found that the spheres were hollow with nothing inside. How could hollow spheres lead to rescue? How did they work?

Here's the answer to the sofar question: Ewing had been studying the ocean, and he was particularly interested in the way that sound travels in water. He knew that the temperature of the water got colder as it got deeper--and that should make sound travel slower. But as you go deeper, the pressure gets stronger, and that should make the sound travel faster. The two effects don't cancel. When he studied it in detail, he concluded that the sound velocity would vary with depth. His most interesting conclusion was that at a depth of about 1 km, the sound travels slower than at any other depth. As we will discuss later, this implies the existence of a "sound channel" at this depth, a layer that tends to concentrate and focus sound and keep it from escaping to other depths. Ewing did some experiments off the coast of New Jersey and verified that this sound channel existed, just as he had predicted.

The sofar spheres were hollow and heavier than an equal volume of water. They sank but were strong enough to hold off water pressure until they reached the depth of the sound channel. At that depth the sphere suddenly collapsed with a bang. That sent out a pulse of sound that could be heard thousands of kilometers away. From these sounds, the Navy could figure out the approximate location of the downed pilot, and send out a rescue team.

It turns out (this wasn't known back then) that Ewing's little spheres used the same phenomena that whales use to communicate with other whales: the focusing of sound in the sound channel. We'll discuss this shortly.

At the end of World War II, the same Maurice Ewing proposed a second project based on the same idea. This project was eventually given the name **Project Mogul**. It used "flying disks" for a highly classified purpose: to detect nuclear explosions. It made use of a sound channel in the atmosphere. But the flying disks crashed in Roswell, New Mexico in 1947, made headlines, and became part of a modern legend.

To explain these stories, we have to get into the physics of sound. And to understand sound, we have to talk about waves.

Waves

All waves are named after water waves. Think for a moment about how strange water waves are. Wind pushes up a pile of water, and the pile creates a wave. The wave moves and keeps on moving, carrying energy far from the place where the wave was created. Waves at the coast are frequently an indicator of a distant storm. But the water from that distant storm didn't move very far, just the wave. The wind pushed the water and the water pushed other water and the energy traveled for thousands of miles, even though the water only moved a few feet.

You can make waves on a rope or with a toy called a *slinky*. (If you've never played with a slinky, you should go to a toy store as soon as possible and buy one.) Take a long rope or a slinky, stretch it across a room, shake one end, and watch the wave move all the way to the other end and then bounce back. (Water waves, when they hit a cliff, also bounce.) The rope jiggles, but no part of it moves very far. Yet the wave does travel, and with remarkable speed.

Sound is also a wave. When your vocal cords vibrate they shake the air. The air doesn't move very far, but the shaking does. The shaking moves as far as the ear can hear and further. The initial shaking air around your vocal cords makes the air nearby shake also, and so on. If the shaking reaches someone else, then it causes his eardrums to shake, which sends signals to his brain and causes him to hear you.

For a nice animation of a sound wave, showing how the molecules bounce back and forth but create a wave that moves forward only, see http://www.kettering.edu/~drussell/Demos/waves/wavemotion.html

If the sound wave hits a wall, it bounces. That's what gives rise to echoes. Sound waves bounce just like water waves and rope waves.

A remarkable thing about all these kinds of waves is that the shaking leaves the location where it started. Shake some air and you create a sound, but the sound doesn't stay around. A wave is a way of transporting energy long distances without actually transporting matter. It is also a good way to send a signal.

It turns out that light, radio, and TV signals also consist of waves. We'll get to that in the next chapter. What is waving for these? The traditional answer is "nothing" but that is really misleading. A much better answer is that there is a "field" that is shaking – the electric and magnetic fields.

Another correct answer is that “the vacuum” is what is shaking. We’ll discuss this further in the chapter on quantum mechanics.[1]

Wave packets

Waves can be long with many vibrations, as when you hum, or they can be short, as in a shout. We call such short waves “wave packets.” You may have noticed water waves often travel in packets. Splash a rock into a pool and you’ll see a bunch of waves moving out, forming a ring that contains several up and down oscillations. That’s a packet. A shout contains many oscillations of the air, but these oscillations are confined to a relatively small region. So that too is a wave packet.

Now think about this: short waves act in a way very similar to particles. They move and they bounce. They carry energy. If the packet were extremely short, maybe you wouldn’t notice that it was really a wave. Maybe you would think it was a small particle.

In fact, the theory of quantum mechanics is really a fancy name for the theory that all particles are really little packets of waves. The packets for an electron and proton are so small that we don’t normally see them. What is waving in an electron? We think it is the same thing that is waving for light: the vacuum.

So when you are studying sound, water, and earthquakes, you are really learning the properties of waves. That will be most of what you need to understand quantum mechanics.

Sound

Sound in air results when air is suddenly compressed, for example by a moving surface (such as a vibrating vocal cord or bell). The compression pushes against adjacent air, and that pushes against the air in front of it, and so on. The amazing thing about sound is that the disturbance travels, and the shaking of the original air stops. The energy is carried away very effectively.

Sound is generated in air when something compresses it in a local region. This could be the vibrating of vocal cords, a violin string, or a bell. The compressed air expands, and compresses the air next to it. The air never moves very far, but the compression is passed on from one region to the next. This is depicted in the following diagram. Each little circle represents a

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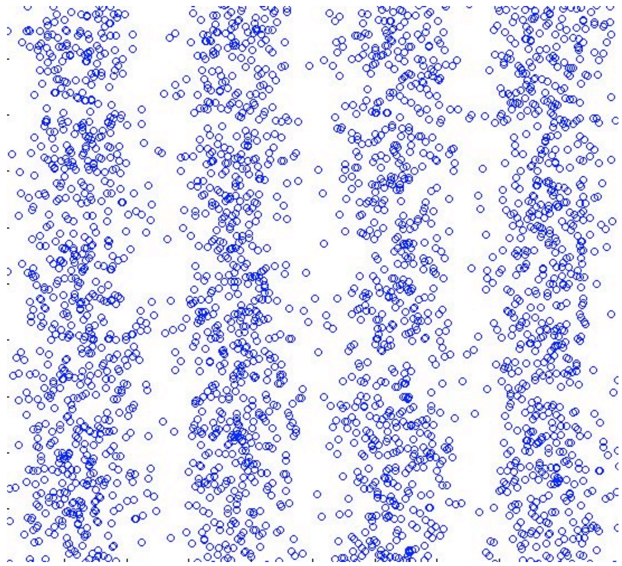
[1] Here is a brief summary of the answer: when it was discovered that light is a wave, physicists didn’t know what was waving, but they gave it a name: the “Aether.” (I spell it this way to distinguish it from the chemical “ether” which is totally different.) Most modern physicists believe that the Aether was shown not to exist, but that isn’t true. The distinguished theoretical physicist Eyvind Wichmann pointed out (in a class I took from him at Berkeley) that the Aether was only shown to be invariant under the laws of special relativity, and therefore was unnecessary. But then quantum mechanics started giving it properties: it can be polarized, and it carries dark energy. Wichmann says that the Aether never went away from physics; it was made more complex, and simply was reborn with a new name: the vacuum.

molecule. The wave consists of compression and expansion of regions of the gas.



Each molecule shakes back and forth, and doesn't travel very far. But the waves travel forward. Look at the diagram, and imagine that you are looking at a series of water waves from an airplane. But the waves in sound don't come from up and down motion, but from compression and dilation. When these compressions reach your eardrum, they make it vibrate. Those vibrations are then passed on through the rest of your ear to nerves and then to the brain, where the vibrations are interpreted as sound.

To understand this, it is easiest to watch a movie. A very nice one is posted at www.kettering.edu/~drussell/Demos/waves/wavemotion.html. A wave is moving from the left to the right. But if you watch one molecule, you'll see that it is shaking back and forth, and never travels very far. It bangs into a nearby molecule, and transfers its energy.

That is the key aspect of waves. No individual molecule travels very far, but the energy is transferred. They pass on the energy, from one to the next. It is the energy that travels long distances, not the particles. Waves are means for sending energy without sending matter.

Sound waves can travel in rock, water, or metal. All those materials compress slightly, and this compression travels and carries away the energy. If you hit a hammer on a railroad rail, then the metal rail is momentarily distorted and the distortion travels down the rail. If someone puts her ear to the rail a mile away, she will hear the sound. The best way to hear the sound is to put your head against the rail. The vibration in the rail will make your skull vibrate, and this will make the nerves in your ear respond--even if none of the sound is actually in air.

Because steel is so stiff, it turns out that sound travels 18 times faster in steel than in air. In air, sound takes 5 s to go 1 mi; in steel, sound will go that same distance in less than 1/3 s. In the olden days, when people lived near railroad tracks, they could listen to the track to hear if a train was coming, and they could even estimate the distance to the train by the loudness of the sound.

For sound to travel, the molecules of air have to hit other molecules of air. That's why the speed of sound is approximately equal to the speed of molecules. We discussed this fact in Chapter 2. But in steel, the molecules are already touching each other. That's why sound in steel can move much faster than the thermal velocity of the atoms in the steel.

Sound travels in any material that is springy, i.e. which returns to its original shape when suddenly compressed and then released. The faster it springs back, the faster the wave moves. The speed of sound in water is about 1 mi/s, but it varies slightly depending on the temperature and depth of the water.

Note that a sound wave in water is a different kind of wave than the water wave that moves on the surface. In water, sound travels *under* the surface, in the bulk of the water. It consists of a compression of the water. Water waves on the surface are not from compression, but from movement of the water up and down, changing the shape of the surface. So although they are both in water, they are really very different kinds of waves. You can see surface waves easily. You usually cannot see sound waves. Surface waves are slow and big. Sound waves are microscopic and fast.

The speed of sound in air doesn't depend on how hard you push, that is, on how intense the sound is! No matter how loud you shout, the sound doesn't get there any faster. That's surprising, isn't it?

Why is that true? Remember, at least for air, the speed of sound is approximately the speed of molecules. The signal has to go from one molecule to the next, and it can't do that until the air molecule moves from one location to another. (The added motion from the sound vibration is actually very small compared to the thermal motion of the molecules.) When you push on the air, you don't speed up the molecules very much; you just push them closer to each other.

But the speed of sound does depend on the temperature of the air. That's because the speed depends on the velocity of the air molecules, and when air is warmer, the velocity is greater.

The table below gives the speed of sound in several materials:

material and temperature	**speed of sound**
air at 0 C = 32 F	331 m/s = 1 mi for every 5 s
air at 20 C = 68 F	343 m/s
water at 0 C	1402 m/s = 1.4 km/s
water at 20C	1482 m/s = almost 1 mi/s
Steel	5790 m/s = 3.6 mi/s
Granite	5800 m/s

There is no need to memorize this table. But you should remember that sound moves faster in solids and liquids than in air. And you should know that the speed of sound in air is about one mile every five seconds.

Sound traveling in rock gives us very interesting information about distant earthquakes. We'll come back to that later in this chapter. Observations of the surface of the sun show sound waves arriving from the other side, traveling right through the middle of the Sun. Much of our knowledge of the interior of the Sun comes from the study of these waves. (We detect them by sensitive measurements of the surface of the Sun.) Sound has been detected traveling through the Moon, created by meteorites hitting the opposite side. On the Moon we use instruments that were left behind by the Apollo astronauts.

There is no sound in space because there is nothing to shake. A famous tag line from the science fiction movie *Alien* (1979) is, "In space, nobody can hear you scream." Astronauts on the moon had to talk to each other using radios. Science fiction movies that show rockets roaring by are not giving the sound that you would hear if you were watching from a distance--since there would be no sound.[2]

Transverse and longitudinal waves

When you shake the end of a rope, the wave travels down its length, from one end to the other. However, the shaking is sideways, i.e. the rope vibrates sideways even thought the direction that the wave is moving is along the rope. This kind of wave is called a *transverse* wave. In a transverse wave, the motion of the particles is along a line that is perpendicular to the direction the wave is moving.

For an illustration of a transverse wave, go back to:
http://www.kettering.edu/~drussell/Demos/waves/wavemotion.html
and look at the second illustration on that page.

A sound wave is different. The vibration of the air molecules is back and forth, in the same direction that the wave is moving. This kind of compressional wave is called a *longitudinal* wave. In such a wave, the motion and direction of the wave are both along the same line.

This may seem peculiar, but water waves are even stranger.

Water surface waves

Water waves (the term we will use when we mean the ordinary surface water waves--as opposed to water sound waves) gave all waves their name. If you are swimming or floating and a water wave passes by, you move slightly back and forth as well as up and down. It is worthwhile to go swimming in the ocean just to sense this. In fact, for most water waves, the sideways motion is just as big as the up and down, and you wind up moving in a circle! But when the wave is past, you and the water around you are left in the same place. The wave, and the energy it carries, passes by you.

For a nice illustration of the motion of particles in a water wave, take a look again at
http://www.kettering.edu/~drussell/Demos/waves/wavemotion.html
but this time scroll down to the third animation. Look at one particle, maybe one of the blue ones, and watch how that particle moves. Does it move in a circle?

When there is a series of waves following each other, we call that a wave packet. The distance between the crests (the high points of the waves) is called the **wavelength**. Waves with different wavelengths travel at very different speeds. Those with a short wavelength go slower, and those with a

[2] To enjoy the movie, I always assume that the microphone is located on the spacecraft, so although we are watching the rocket pass, we are hearing sound as if we were on the rocket.

long wavelength go faster. In deep water (when the depth is greater than the wavelength), the equation is as follows:[3]

$$v \approx \sqrt{L}$$

In this equation, v is the velocity in meters per second (m/s), and L is the wavelength in meters (m), and the squiggly equals sign ≈ means "approximately equal to." So, for example, if the wavelength (distance between crests) is L =1 m, then the velocity is about v = 1 m/s. If the wavelength is 9 m, the velocity is 3 m/s. Does that agree with your image of ocean waves? Next time you swim in the ocean, check to verify that long waves move faster.

That equation is remarkably simple, but it is correct only for deep water, that is, for water that is much deeper than a wavelength.

Shallow water waves

When the water is "shallow" (the depth D is much less than the wavelength L) then the equation changes to

$$\begin{aligned} v &= 3.13\sqrt{D} \\ &\approx \pi\sqrt{D} \end{aligned}$$

where D is the depth in meters.[4] Note that all shallow water waves travel at the same velocity, determined only by the depth of the water, regardless of the wave's wavelength. The speed of shallow water waves depends only on the depth of the water. This might match your experience when you surf on relatively long waves in shallow water.

If the wavelength is very long, then we have to regard even the deep ocean as shallow. This is often the case for tsunamis.

Tsunamis (tidal waves)

A tsunami is a giant wave that hits the coast and washes far up on the shore, often destroying buildings that are within a few hundred meters of the beach. Tsunamis were traditionally called tidal waves, but a few decades ago scientists (and newspapers) decided to adopt the Japanese word, and now it is more commonly used.

Underwater earthquakes and landslides often generate tsunamis. These waves usually have a very high velocity and a very long wavelength. In the deep ocean, they may have a very low amplitude, so they can travel right under a ship without anyone on board even noticing. But as they approach land, they are slowed down, and the energy is spread out over a smaller depth of water. As a result, the height of the wave rises. The rise can be enormous, and that is what causes the damage near the coast.

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[3] *For the physics major*: The standard physics equation for deep water waves is v = sqrt(gL/(2π)), where g = 9.8 m/s^2 is the acceleration of gravity (from Chapter 3). Putting in g = 9.8, gives v ≈ 1.2 sqrt(L) ≈ sqrt(L).

[4] The second equation is only approximate. I wrote it using the symbol π to make it easier to remember, even though you don't have to remember it.

In Pacific islands (such as Hawaii) you'll see sirens mounted on poles near the beaches. If an earthquake is generated within a few thousand miles, these sirens will be sounded to warn the residents to evacuate. A tsunami could arrive within a few hours.

If a very large earthquake fault moves underneath deep water, the wave it creates can be very long. For a large tsunami, a typical wavelength is 10 km, although some have been seen with wavelengths of 100 km and more. That means even in water with a depth of 1 km = 1000 meters, a tsunami is a *shallow* water wave! (Recall that a "shallow water wave" is one in which the wavelength is greater than the depth.)

The velocity of the tsunami can be calculated from the shallow water equation. In water, 3 km deep, $D = 3000$ meters, so the velocity is $v = 3.13$ sqrt(3000) ≈ 171 meters per second. That's 386 miles per hour, about half as fast as the speed of sound in air. A tsunami that is generated by an earthquake 1000 mi away will take 2.6 hours to arrive. That's enough time to give warning to coastal areas that a tsunami is on its way.

You can outrun a tsunami

Imagine a tsunami with that velocity, with a wavelength of 30 km. Imagine that one crest of the wave passes you. The next one is approaching you from 30 km away. Even with its speed of 313 m/s, it will take $t = d/v = 30000/313 = 100$ s to reach you. The water will fall for the first 50 of these seconds, and then rise for the next 50. Thus, although these waves travel fast, they are slow to rise and fall. That's why tsunamis were called tidal waves. If you are in a harbor, and there is a small tsunami, it might take 100 s for the water to rise and fall, and it gives the appearance of a rapid tide. The image of a huge breaking wave hitting the shore is largely fictional; most tsunamis are just very high tides that come and wash away everything close to the shore.[5] That's how they do their damage. If the ocean rises 10 m, it destroys everything, even if it takes 50 s to reach its peak. If you are young and healthy, you can usually outrun the rising water as it comes in. If you are not fast enough, then you get swept up in a very large volume of water, and dragged out to sea when the wave recedes. Small tidal waves are frequently observed as slow (100 s) rises and falls in harbors. Boats tied to docks are often damaged by these slow waves as they rise above the dock and get thrown into other boats. Many captains take their boats out into the harbor or out to sea when they are alerted that a tsunami is coming. In Japanese, the word "tsunami" means "harbor wave."

The equation for waves

Recall from the last section that if the wavelength is L, and the velocity is v, then the time it takes between crests hitting you is $T = L/v$. The time T is called the **period** of the wave. This calculation is true for all waves, sound,

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[5] The tsunami in the movie *Deep Impact* (1998) is particularly inaccurate. It shows a giant wave breaking over Manhattan Island. But the harbor of New York City is relatively shallow; there is no place for that much water to come from, unless a giant wave broke far out to sea.

tsunamis, deep water waves, even light waves. It is the fundamental relationship between velocity, period, and wavelength.

$$T = L/v$$

If the period is less than one second, it is usually more convenient to refer to the number of crests that pass by every second. That is called the ***frequency*** f of the wave, and it is given by f = 1/T. Putting these into the above equation, we get 1/f = L/v, or

$$v = f\,L$$

You don't have to memorize this equation, but we will use it a lot, especially when we discuss light. Light in vacuum has a speed $v = 3 \times 10^8$ m/s, a number we usually call *c*. Since we know *c*, the equation allows us to calculate the frequency whenever we know the wavelength, or the other way around.

Sound doesn't always travel straight

Sound waves, whether in air or in ocean, often do not travel in straight lines. They will bend upwards or downwards, to the left or to the right, depending on the relative sound speed in the nearby material. Here is the key rule:

> **Waves tend to change their direction by bending their motion towards the side that has a slower wave velocity.**

To understand why this is so, imagine that you are walking arm-in-arm with a friend. If your friend is on your left side and slows down, that pulls your left side backwards and turns you towards the left. If your friend speeds up, that pulls your left arm forward and turns you to the right (and also turns your friend to the right). The same phenomenon happens with waves. A more complete description of this is given in the optional section at the end of the chapter about Huygens's principle.

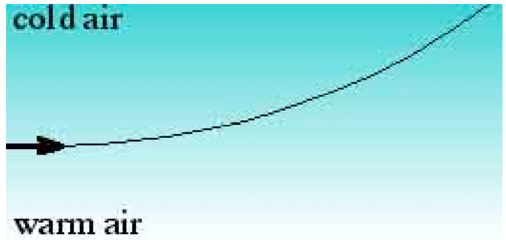
This principle can be demonstrated in a large classroom by having students raise their hands as soon as their neighbor raises a hand. The location of students' hand-raising moves throughout the classroom like a wave. This procedure is popular among fans in sporting events, where it is also called a "wave." If the students in one part of the room are told to be a little slower, then the wave will bend towards them as it spreads across the room.

The direction changing rule is true for all kinds of waves, including sound, water surface waves, and even earthquakes and light.

Example: "normal atmosphere"

Here is an example from the atmosphere. At high altitude, the air is usually colder. That means that the velocity of sound at high altitude is slower than it is at low altitude.

Now imagine a sound wave that is initially traveling horizontally, near the surface of the earth. Above it, the velocity is lower, so it will tend to bend upward. This is shown in the following diagram.

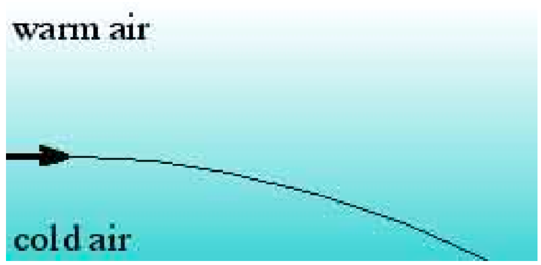


Cool atmosphere near the warm ground. Sound bends upward.

Notice that the sound bends away from the ground towards higher altitude. It bends upward. That's because the air above it has a slower sound velocity.

Sound in the evening

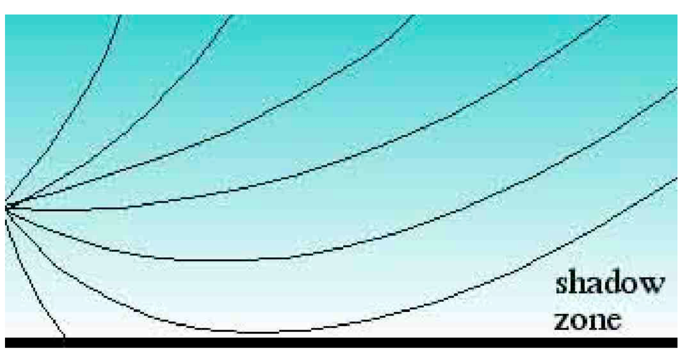
When the sun sets, the ground cools off rapidly. (It does this by emitting infrared radiation; we'll discuss this further in the Chapter 9 "Invisible Light.") The air does not cool so quickly, so in the evening, the air near the ground is often cooler than it is up higher. This phenomenon is called a "temperature inversion" because it is opposite to the normal pattern of the daytime. When there is a temperature inversion, sound tends to bend down towards the ground, as shown in the following figure.



Sound near the ground when there is an inversion

Sound during the day, again

Now let's look at the morning situation again, with warm air near the ground and cold air up high. But let's draw many sound paths, all coming from the same point. This is done in the diagram below.

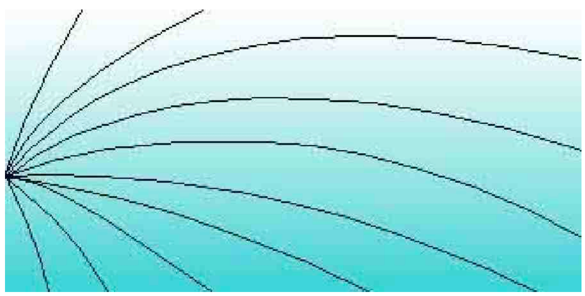


The solid line at the bottom represents the ground. Note that it blocks certain paths--the ones that drop too steeply. In the lower right corner is a small region that none of the paths can reach, since to reach this region the sound waves would have to go through the ground. (We'll assume for now that the ground absorbs or reflects sound, and does not transmit it, at least, not very well.) If the sound were coming from the point on the left, and you were standing in the shadow zone, then you wouldn't hear any sound at all. You are in the sound shadow of the ground.

This diagram shows why mornings tend to be quiet. Sounds bend up toward the sky, and if you are near the ground, there is no way that most of them can reach you. You won't hear distant automobiles, birds, waves, lion roars…

Sound in the evening, again

In the diagram below, I've redrawn the evening situation, with the inverted temperature profile (cold at the bottom, warm at the top).



Note that there is no shadow zone. No matter where you stand, there are paths by which the sound can reach you.

Have you ever noticed that you can hear more distant sounds in the evening than in the morning? I've noticed that in the evening I can often hear the sound of distant traffic, or of a train; I rarely hear such sounds in the morning. (This phenomenon first mystified me when I was a teenager living 1/4 mile from the beach. I noticed that I could hear the waves breaking in the evening, but almost never in the morning.)

The explanation is in the diagrams above: in the evening, sound that is emitted upward bends back down, and you can hear sound from distant places. There is no shadow zone.

If you happen to be a wild beast, then the evening would be a good time to search for prey, since you could hear it even when it was far away.

Forecasting a hot day

There are times when I wake up in the morning and hear distant traffic. Then I know that it will probably be a hot (and maybe smoggy) day. I learned this from experience long before I figured out the reason why.

The reason is that hearing distant sounds means there is an inversion, i.e. the high air is warmer than the low air. The sound diagram for an inversion in the morning is identical to the sound diagram shown above for the evening.

Inversions are unusual in the morning, but they do happen. The presence of an inversion in the morning leads to a special weather condition. On normal (no inversion) days, hot air is near the ground, and cold air is above it. Hot air is less dense than cold air, so it tends to float upward. (In the same way, wood floats on water if it is less dense than water.) So the hot air tends to leave the ground, replaced by cooler air from above.

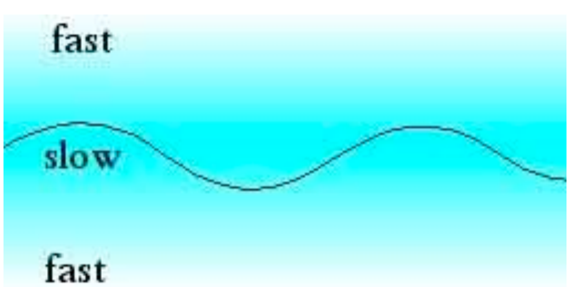
But if there is an inversion, i.e. there is hot air above and cold below, then the air above is less dense than the air at the ground. So convection, the floating of the ground air upward, doesn't take place. With no place to rise to, the hot air accumulates near the ground, making for a hot day. Smog and other pollutants also accumulate. The weather forecast on the radio or TV will often announce that there is an "inversion." Now you know what that means: the normal temperature profile is inverted, i.e. it is upside down with the cool air near the ground and warm air above.

Inversions frequently happen at the end of a hot day. The ground cools more rapidly than does the air (that's because it emits IR radiation; we'll discuss that in the next chapter). The air near the ground is cooled by contact with the cool ground, and the air above remains warm (unless there is turbulence from wind). For people who are sensitive to smog, the announcement of an inversion is bad news. For people who love hot weather, it is good news.

The sound channel explained: focused sound

Now let's get back to the mysterious sound channel in the ocean that Maurice Ewing exploited for his sofar system in World War II.

In the ocean, the temperature of the water gets cooler as we go further down. This would make the speed of sound less. But, as mentioned earlier, the water is also getting more and more compressed (i.e. denser) because of the increasing pressure. This tends to make sound go faster. When these two effects are combined, we get a gradual decrease in sound velocity as we go from the surface to about 1 km of depth, and then the sound velocity increases again. This is illustrated in the diagram below. Darker means slower sound (just as it did in the atmosphere diagrams).



I've also drawn the path of a ray of sound. Notice that it always bends towards the slow region. The path I drew starts with an upward tilt, bends downward, passes through the slow region, and then bends upward. The path oscillates up and down, but never gets very far from the slow region, the 1 km-deep sound channel.

Exercise: Draw some other paths, starting at different angles. What happens if the ray starts out horizontally? Vertically?

How Sofar saved downed pilots

Let's return now to the magic of Ewing's sofar spheres. As I stated earlier, they were hollow, and yet they were made of heavy material. Since they weighed more than an equal volume of water, they didn't float, but sank. Ewing designed the spheres to be strong enough to withstand the pressure of water down to a depth of 1000 m. At this depth, the spheres were suddenly crushed. (Like an egg, the round surface provides lots of strength, but when it breaks, it breaks suddenly.) The water and metal collapsed, and banged against the material coming in from the other side. It's like a hammer hitting a hammer, it generates a loud sound. The energy released from a sphere with radius of 1 in at a depth of 1 km is approximately the same as in 60 mg of TNT. That doesn't sound like a lot--but it is about the same amount you might find in a very large firecracker.

In the air, the sound of a firecracker doesn't go far, perhaps a few kilometers. But at a depth of 1000 m, the ocean sound channel focuses the sound. Moreover, the sound channel is quiet. Sound doesn't get trapped unless it originates within the sound channel itself. (Can you see why?) Any sounds created in the sound channel by whales or submarines stay in there, so the sound doesn't spread out as much as it would otherwise. Microphones placed within the sound channel can hear sounds that come from thousands of kilometers away.

During World War II, the Navy had arranged for several such microphones placed at important locations, where they could pick up the ping of the imploding Ewing spheres. They could locate where the implosion had taken place by the time of arrival of the sound. If the sound arrived simultaneously at two microphones (for example), then they knew the sound had been generated somewhere on a line that is equally distant from the two microphones. With another set of microphones they could draw another line, and the intersection of the two lines gave the location of the downed pilot.

Historical note: "Sofar" supposedly stands for "**SO**und **F**ixing **A**nd **R**anging." Fixing and ranging was Navy terminology for determining the direction to a source (that's the fixing part) and its distance (ranging). Despite all this, I suspect that the acronym was forced, and the real name came about because the channel enabled you to hear things that were *so far* away. Some people still refer to the sound channel as the sofar channel. I learned about the sofar spheres from Luis Alvarez, who knew about them from his scientific work during World War II. I have spoken to several other people who remember them, including Walter Munk and Robert C. Spindel. Spindel believes that the spheres contained a small explosive charge to enhance the sound. We have not yet found any historical documentation that verifies this.

Whale songs

What does the sound channel look like? The word "channel" can be misleading, since it brings up a vision of a narrow corridor. It is not like a tube. It is a flat layer, existing about a kilometer deep, spreading over most of the ocean. Sound that is emitted in the sound channel tends to stay in the sound channel. It still spreads out, but not nearly as much as it would if it also spread vertically. That's why the sound can be heard so far away from its source. It tends to get focused and trapped in that sheet.

In fact, the sound channel is like one floor in a very large building, with ceiling and floor but without walls. Sound travels horizontally, but not vertically. If sound is emitted at the surface of the ocean, then it does not get trapped. So the sound of waves and ships does not pollute the sound channel. The sound channel is a quiet place for listening to sofar spheres and other sounds that are generated in the sound channel.

Whales discovered this, probably millions of years ago. We now know that whales like to sing when they are at the sound channel depth. These songs are hauntingly beautiful. If your computer has the right software, you can listen here to the recorded song of the humpback whale at

www.muller.lbl.gov/teaching/physics10/whale_songs/humpback.wav

and of the gray whale at

www.muller.lbl.gov/teaching/physics10/whale_songs/gray.wav

You can find other recordings on the Internet, and you can buy recordings on CDs. Nobody knows what the whales are singing about. Some unromantic people think they are saying nothing more than "I am here."

Global Positioning System (GPS)

A favorite gadget for hikers, boaters, and travelers is a Global Positioning System (GPS) receiver. This is a small device that will tell you where you are on the earth, to an accuracy of a few feet. You can buy one at a sporting goods store for about $100. If you rent a car, for a small charge you can get one with GPS built in--to help keep you from getting lost. Many new cars now come equipped with GPS and a built in map system.

Why am I talking about GPS? Because GPS uses the same idea that Maurice Ewing used for locating pilots. For GPS, however, the signals are sent using radio waves rather than sound. And instead of using microphones set on the edges of the ocean, it uses radio receivers orbiting the Earth.

The GPS system works because there are now about 24 GPS satellites in space that are emitting signals. Each signal contains the time when it was emitted and the position of the satellite when it was emitted. The GPS receiver has a small computer and an accurate clock.

When the GPS receiver detects a signal, it looks at the time, reads the message saying when the signal was emitted, compares it with its own clock, and determines how long the signal was traveling. It multiplies that by the speed of light, and that gives it the distance to the first satellite. Of course, it also knows exactly where that satellite was when it emitted the signal. Once the GPS knows its distance from three different satellites, it can use geometry to calculate where it is. Can you see why that works?

GPS geometry

How does the GPS system get its location by knowing the distance to three satellites? It's easy to see by analogy. Suppose you didn't know where you were in the US, but knew that you were 1000 mi from Denver and 1500 mi from San Francisco. To pin point your positions, you could first get a map and draw a circle around Denver with a 1000-mile radius. Then draw a 1500-

mile circle around San Francisco. The circles intersect at two points. If you knew your distance to one other city, you would know which of those two points represents your location.

If the GPS receiver gets a signal from four satellites, then it can see if the distance to that satellite is exactly what it expected. It should come out right--since the GPS already knows its own position. Suppose it turns out to be wrong? The only explanation can be that the clock in your inexpensive GPS receiver has drifted and is no longer accurate. So the receiver can use the fourth satellite to adjust its clock! The result is that if it can pick up four satellites, the receiver does not need an accurate clock.

The Cold War and SOSUS

During World War II, the part of the military that used submarines was called "The Silent Service." This reflected the fact that any sound emitted by a submarine could put it in danger of detection, so submariners trained themselves to be very quiet. Someone in a sub who drops a wrench makes a sound that is unlike any other in the ocean. (Fish don't drop wrenches.) The wrench clatters against the hull, and the hull carries the sound to the water, and the vibrations of the hull send the sound into the ocean. Ships on the surface, and other submarines, had sensitive microphones to listen to possible sounds emitted from submarines.

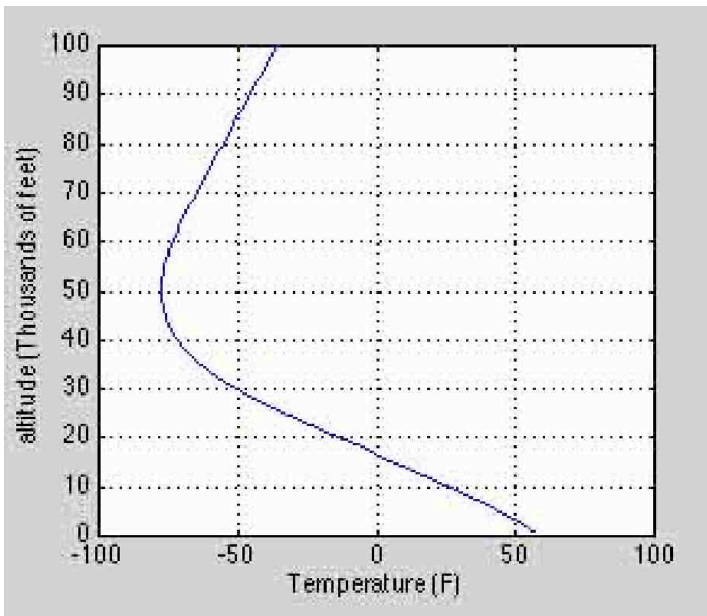
The presence of the sound channel did not remain secret for long, but its properties did. In the period from the 1950s to 1990s, the United States spent billions of dollars to put hundreds of microphones into the channel at locations all around the world. These microphones carried the signals back to an analysis center, and then the world's best computers analyzed them. The system was called SOSUS, an acronym for "SOund SUrveillance System." The magnitude of the SOSUS effort was one of the best kept secrets of the Cold War. Effective use of SOSUS required the Navy to make extensive measurements of the ocean and its properties, and to update the temperature profile of the ocean all around the world. (The ocean has weather fronts analogous to those in the atmosphere.)

Optional--Book to read: If you really want to know more about this subject, one of the best introductions is the novel *The Hunt for Red October* by Tom Clancy. (Not the movie. The movie skips all the interesting technology.) When this novel came out in 1984, much of the material in it was still classified. Clancy had a talent for reading documents, talking to people, and figuring out from what they said and what was really true. The book was so detailed and so accurate (although it does have some fiction in it and some errors) that new people joining the submarine service were told to read the book in order to get a good picture of how operations worked! Many of the details of the SOSUS system were finally declassified in 1991, seven years after Clancy's book was published. The SOSUS system was one of the largest and most expensive secret systems any nation ever built.

Back to UFOs:
a sound channel in the atmosphere!

Soon after he did his work in the ocean, Maurice Ewing realized that there should be a sound channel in the atmosphere! His reasoning was simple: as you go higher, everyone knows the air gets colder. Mountain air is colder than sea level air. The temperature of the air drops about 4 F for every 1000 ft of altitude gain.

That means that the velocity of sound decreases with altitude. But he also knew that when you get to very high altitudes, the temperature begins to rise again. Starting at about 40-50,000 ft, the air starts getting warmer. This is shown in the following figure.



Remember that the speed of sound depends on the temperature of the air. When the temperature is low, so is the speed of sound. That means that the speed of sound is fast at both high and low altitudes, and slower at about 50,000 ft.

Look at the diagram above the previous one, the diagram that showed sound moving in a wiggly line through the ocean. Exactly the same diagram can be used for sound in the atmosphere. That means that there is a sound channel in the atmosphere, centered at about 50,000 ft. (The exact altitude depends on latitude, as well as on the season of the year.) This is what Ewing figured out. He had an important US National Security application in mind to take advantage of this realization.

But first, we need a little more physics. Why does the atmosphere get warmer above 50,000 ft?

Ozone: The cause of the high altitude heating

Why is high altitude air hot? The reason is the famous ozone layer. At about 40-50,000 ft, there is an excess of ozone, and this ozone absorbs much of the ultraviolet radiation from the sun. Ultraviolet is that part of sunlight that is more violet than violet. This light is there, but invisible to the human eye. The ozone layer protects us, since ultraviolet light can induce cancer if absorbed on the skin. We'll talk more about the ultraviolet radiation in Chapter 9 "Invisible Light."

At the end of the 20th century, scientists began to fear that the ozone layer could be destroyed by human activity, and that would let the cancer-causing, ultraviolet radiation reach the ground with greater intensity. In particular, the scientists worried about the release of certain chemicals into the atmosphere called CFCs (chlorofluorocarbons, used in refrigerators and air conditioners). CFCs release chlorine and fluorine, and these catalyzes the conversion of ozone O_3 into ordinary O_2. (To balance the equation, 2 molecules of O_3 turn into 3 molecules of O_2.)

The use of CFCs was outlawed internationally, and that was expected to solve the problem. For this reason, the human destruction of the ozone layer is no longer considered an urgent problem. For more, see chapter 9.

Looking at the ozone layer (and the sound channel): thunderhead tops

On a day where there are large thunderstorms, you can see where the ozone layer is--right at the top of the tallest thunderheads. A thunderstorm grows from hot air at the ground, rising up through the colder (and denser) air above it. When the warm air hits the warm air of the ozone layer, it no longer rises. The cloud spreads out, making the "anvil head" shape that people associate with the biggest storms. So when you see the flat top of a large thunderhead cloud, you are looking at the ozone layer, and at the middle of the sound channel.

Think of it this way: there is a permanent "inversion" of atmospheric temperatures, if you go all the way up to 50,000 ft. That inversion prevents rising air from going any further, just as the low altitude inversion can prevent smog and hot air from rising away from the ground.

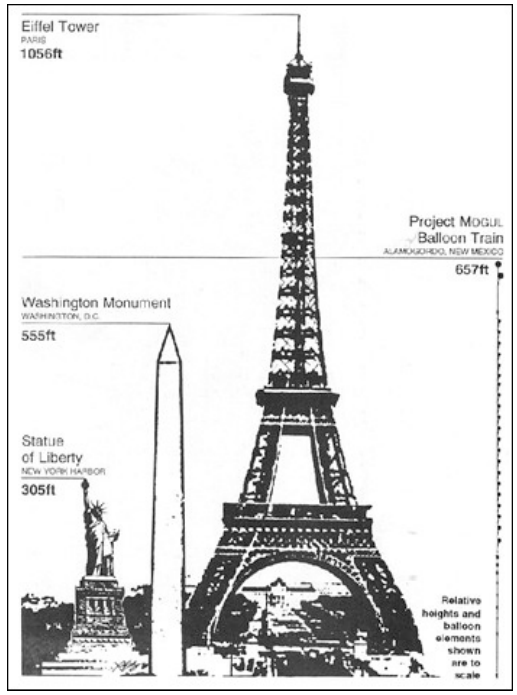
Image of an "anvil head" thunderstorm. The ozone layer and the sound channel are at the top of the cloud. (NOAA photo)

Ewing's Project Mogul and his flying disks

Maurice Ewing had an urgent application for his predicted atmospheric sound channel: the detection of nuclear tests in Russia. In the late 1940s, the Cold War had begun and there was growing fear in many countries of the totalitarian communism represented by Russia. The Russians had great scientists and there was widespread belief that they would be building an atomic bomb soon. At that time, Russia was a very secret and closed society. In fact, Stalin was starving to death 30 million "kulak" farmers, and he could get away with it because he controlled information going in and out of the nation. In 1948, George Orwell wrote *1984*, expressing his fears of such a government.

Ewing realized that as the fireball from a nuclear explosion rose through the atmospheric sound channel, it would generate a great deal of noise that would travel around the world in the channel. (Not all of the sound *bang* is generated when the bomb detonates. The roiling fireball continues to generate sound as it reaches the atmospheric sound channel.) Ewing argued that we should send microphones up into the sound channel to detect and measure any such sound. That way we could detect Soviet nuclear tests, even with microphones in the United States!

The microphones that he used were called "disk microphones." You can see them in photographs of old radio shows. For an old photo of a disk microphone, see
www.muller.lbl.gov/photos/DiskMicrophone.jpg
There is also a photograph of a somewhat smaller disk microphone used by Orson Wells in his famous 1938 broadcast of War of the Worlds, when he actually convinced many listeners that the world was under attack by Martians! For a photo, see
www.muller.lbl.gov/photos/DiskMicWelles3.jpg
You'll also see lots of disk microphones in the movie The Aviator (2004).



The Project Mogul chain of microphones and balloons, compared in size to monuments. (From the US Air Force "The Roswell Report", 1995.)

Ewing's idea was to string the microphones under a high altitude balloon, have them pick up the sounds in the sound channel, and then radio the sounds back to the ground. The disk microphones were called "flying disks." (The word flying was not confined to airplanes; it was equally used by ballooners when they went up.) The balloons were huge, and the string of microphones was 657 ft long, longer than the Washington Monument is high.

The project was a success. The system detected American nuclear explosions, and on August 29, 1949, it detected the first Russian test.

The Roswell crash of 1947

One of the Project Mogul balloon flights crashed near the Roswell Army Air Force base on July 7, 1947. It was recovered by the U.S. Army, who issued a press release stating that "flying disks had been recovered." The Roswell

Daily Record had headlines the next day. We referred to these at the beginning of this chapter: "RAAF Captures Flying Saucer".

The fallen object was not a flying saucer, it was a complex balloon project that carried flying disk microphones to pick up Russian nuclear explosions. The program was highly classified, and the press release said more than the security people considered acceptable, so the next day the press release was "retracted." A new press release stated that what had crashed was a "weather balloon." It wasn't a weather balloon. The US Government was lying.

The government finally tells the truth

In 1994, at the request of a congressman, the U.S. government declassified the information they had on the Roswell incident, and prepared a report. Popular articles appeared in The New York Times, Popular Science(June 1997). But the Official U.S. government report (synopsis only) on Project Mogul is also available at
http://muller.lbl.gov/teaching/physics10/Roswell/USMogulReport.html
See also the official U.S. government report on the Roswell Incident at:
http://muller.lbl.gov/teaching/physics10/Roswell/RoswellIncident.html

Of these articles, you should read at least the New York Times article. The Popular Science articles give interesting background. The official U.S. government reports give details that you might find interesting.

Should the US Government ever lie? This is just the sort of issue that you should confront *before* you become president! It would make a good discussion question.

How do we know the government isn't lying now?


Richard Muller examines something interesting in the UFO Museum, Roswell, New Mexico

Many people believe the official government report on Project Mogul is just an elaborate cover-up. They believe that a flying saucer really did crash, and the government doesn't want the public to know. Maybe I am part of this conspiracy, and part of my job is to mislead you into believing that flying saucers don't exist! (According to the movie *Men in Black* (1997), the job of the Men in Black is to make sure the public never finds out.)

I suggest the following answer: the people who continue to believe that Project Mogul never happened probably don't understand the remarkable science of the ocean and atmosphere sound channels. I could not have invented such a wonderful story. It has too many amazing details. In contrast, it is relatively easy to make up stories about flying saucers. Those don't require much imagination. So here is my hypothesis: it is possible to distinguish the truth by the fact that it is more imaginative and more fascinating!

Of course, I might be lying. At left is a photograph taken of me at the UFO museum in Roswell, New Mexico in 2007.

Earthquakes

When a fault in the Earth suddenly releases energy, it creates a wave in the ground. The location where an earthquake starts is called the epicenter. Most people who experience an earthquake are far from the epicenter, and are shaken by the wave that starts at the epicenter and shakes them as it passes by.

The epicenter of an earthquake can be located by noting when the earthquake wave arrived at several different locations--just as the sofar disks were used to locate downed pilots in World War II. Moreover, the epicenter is often deep underground, so even someone who is standing at the latitude and longitude of the epicenter can be standing over 15 miles away from it (i.e. above it).[6]

Huge amounts of energy are released in earthquakes, often greater than in our largest atomic weapons. That shouldn't surprise you. If you are making mountains shake over distances of tens or hundreds of miles, it takes a lot of energy. In 1935, Charles Richter found a way to estimate the energy from the measured shaking. His scale, originally called the Magnitude Local, became known as the Richter scale. An earthquake with magnitude 6 is believed to release the energy equivalent of about 1 million tons of TNT. That is the energy of a large nuclear weapon. Go up to magnitude 7 (roughly that of the Loma Prieta earthquake that shook San Francisco and the World Series in 1989) and the earthquake releases energy 10 to 30 times greater.

Why do I say a factor of 10 to 30? Which is it? The answer is that we don't really know. Magnitude is not exactly equivalent to energy. For some earthquakes, a magnitude difference of 1 unit will be a factor of 10, and for others it will be a factor of 30. It is easier to determine magnitude than it is to determine energy, and that's why magnitude is so widely used.

In the table on the next page I give the approximate magnitudes of some historical earthquakes in the US. I rounded them off to the nearest integer.

Earthquake	Approximate magnitude	Megatons of TNT
	6	1
San Francisco area 1989	7	10 to 30
San Francisco 1906	8	100 to 1000
Alaska 1999	8	100 to 1000
Alaska 1964	9	1000 to 30,000
New Madrid Missouri 1811	9	1000 to 30,000

Waves transport energy from one location to another. The velocity of an earthquake wave depends on many things, including the nature of the rock or soil in which it is traveling (granite? limestone?), and its temperature (particularly for earthquakes traveling in deep rock).

An especially deadly effect occurs when a wave moves from high velocity material into low velocity material, such as from rock to soil. When a wave slows down, its wavelength (the spacing between adjacent crests) decreases. But the energy is still there, but now squeezed into a shorter distance. That increases the amplitude of the shaking. Even though the

[6] "Shallow" earthquakes are defined to be those less than 70 km deep.

energy carried by the wave is unchanged, the effect on buildings becomes much stronger. This is what happened in downtown Oakland in the 1989 Loma Prieta quake. The earthquake wave passed right through much of Oakland without causing great damage, until it reached the area near the freeway. This region had once been part of the bay, and had been filled in. Such soft ground called "landfill" has a slow wave velocity, so the amplitude of the earthquake increased when it reached this ground. The most dangerous areas in an earthquake are regions of landfill. The Marina District in San Francisco is also landfill, and that is why it was so extensively damaged.

Personal story from the author: My daughters were at the Berkeley WMCA when the 1989 Loma Prieta earthquake hit. One of them told me that she was thrown up against the wall by the earthquake. I said to her, "No, Betsy, that was an illusion. You weren't thrown against the wall. The wall came over and hit you."

Locating the epicenter of an earthquake

You already know that you can measure the distance to a lightning flash by counting the seconds and dividing by 5. The result is the distance to the lightning in miles. But here is another trick: as soon as you feel the ground shaking, and as you are ducking for cover, start counting seconds. When the bigger shaking finally arrives, take the number of seconds and *multiply* by 5. That will give you the distance to the epicenter (the place where the earthquake started) in miles.

Why does that work? To understand it, you should know that in rock, there are three important kinds of seismic waves. These are the P wave, the S wave, and the L wave.

The P wave
(primary, pressure, push)

P stands for "primary" because this wave arrives first. This is a longitudinal (compressional) wave, as is ordinary sound. That means that the shaking is back and forth in the same direction as the direction of propagation. So, for example, if you see that the lamppost is shaking in the east-west direction, that means that the P wave is coming from either the East or the West. Some people like to use the memory trick that the P wave is a Pressure wave, i.e. it is like sound because it is a compression and rarefaction, rather than a transverse motion. The P wave travels at about 6 km/s = 3.7 mi/s. That is a lot faster than the speed of sound in air (which is 300 m/s = 0.3 km/s).

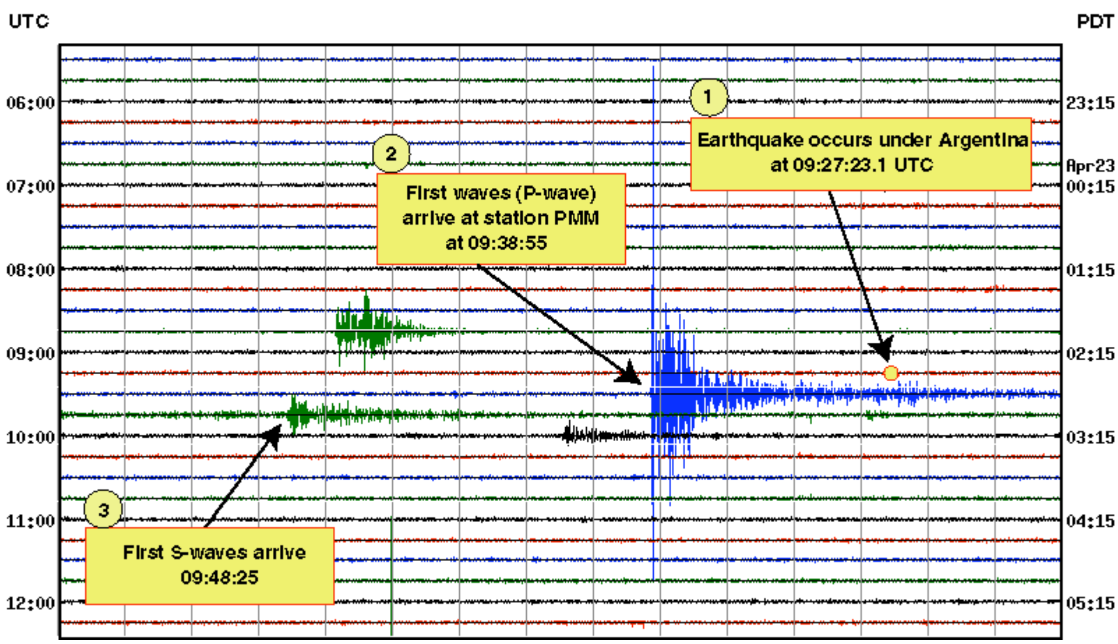
The S wave
(secondary, shear)

S stands for "secondary" because this wave arrives second. This is a transverse wave. That means that the shaking is perpendicular to the direction of propagation. If the wave is traveling from the east, then this implies that the shaking is either north-south, up-down, or some angle in between. Some people like to use the memory trick that the S wave is a shear wave, i.e. it can only propagate in a stiff material which does not allow easy shear motion (sideways slipping). Liquids do not carry shear waves. We know there is a liquid core near the center of the Earth because shear waves do not go through it. The S wave travels at about 3.5 km/s = 2.2 mi/s.

The L wave (long, last)

L stands for "long." These are waves that travel only on the surface of the Earth. Like water waves, they are a combination of compression and shear. They are created near the epicenter when the P and S waves reach the surface. They are called long because they tend to have the longest wavelength of the three kinds of seismic waves. It is the L wave that usually does the most damage, because the wave traveling on the surface often retains the biggest amplitude since it is not spreading out into three dimensions. The L wave travels at about 3.1 km/s = 2 mi/s. Some people like to use the memory trick that the L wave is the last to arrive. (Careful with memory tricks. The L wave is NOT a pure "longitudinal" wave!)

The image below shows the shaking of the ground caused by a distant earthquake. Look at the wiggly line that crosses the image near the top. That is the first line, and it shows the shaking measured by the seismograph. Later lines are below this one. The little circle shows when the earthquake actually took place, at 9:27:23 UT. (UT stands for "universal time", and it is the time at Greenwich UK.) The first shaking, due to the P wave, actually reaches the seismograph about 11 minutes later (shown as point 2). The S wave arrives about 10 minutes after that. There is no evidence for an L wave.



For a nice animation of the L wave (also known as the Rayleigh wave) go to:
http://www.kettering.edu/~drussell/Demos/waves/wavemotion.html
and look at the fourth animation on the page. If you look at the blue dots, you'll see they move in circular-like patterns (they are actually ellipses). At the top of the wave, the circle moves backwards – that is, opposite to the

direction the wave is moving! That's the opposite of what you saw in a water wave. And, if you go deep enough, the motion is forwards. Very strange.

distance to the epicenter, again

Let's return now to the method of estimating the distance to the quake. As you are ducking under a table, start counting seconds from when you felt the first tremor, i.e. the P wave. (You can get very good at doing this if you live in California long enough.) When the S wave arrives then you know:

For every second, the epicenter is about 8.4 km = 5 mi away.

This is the rule I mentioned earlier. Thus if there is a 5-second gap between the waves, the epicenter was 5x5 = 25 mi away. You may even be able to estimate the direction from the P wave shaking--the back and forth motion is in the same direction as the source. If we are lucky enough to have an earthquake during class, then you can watch me do this. (This equation is not true for travel through the deep earth, where the velocities are faster.)

For those of you who like math, can you see how I got the value of 8.4? It is based on the P and S velocities. *Hint*: the distance a wave travels is equal to the velocity multiplied by the time. This calculation is optional (not required) and relegated to a footnote.[7]

There are small earthquake waves passing by all the time, just as there are small waves everywhere you look on the ocean surface. To see the waves recorded for the last few hours, look at the University of California Berkeley Seismograph record at http://quake.geo.berkeley.edu/ftp/outgoing/userdata/quicklook/BKS.LHZ.current.gif This is an extremely interesting link to keep on your computer; it is something you can check any time you think you might have felt a quake. (Wait a little while before checking, the online plot is only updated every few minutes.) You'll see it there, even when it is not reported on the news. The quakes that occur every day in this region are also available on a map: http://quake.wr.usgs.gov/recenteqs/

The liquid core of the Earth

Halfway to the center of the Earth, about 2900 km deep (1800 mi) is a very thick layer of liquid. (The distance to the center of the Earth is 6378 km.) You could say that the entire earth is "floating" on this liquid layer. The layer is mostly liquid iron, and the flow of this liquid creates the Earth's magnetic field (as discussed in Chapter 6). The liquid is so hot, that if we didn't have

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[7] Suppose an earthquake is at a distance d from where you are standing. The P wave moves with a velocity v_P. The time it takes the wave to reach you is $T_P = d/v_P$. The S wave moves with a velocity v_S. The time it takes to reach you is $T_S = d/v_S$. First you feel the P wave, and you start counting seconds. Then the S wave arrives. The time difference that you measured is $T = T_S\text{-}T_P$. According to our equations, this is $T = T_S\text{-}T_P = d/v_S\text{-}d/v_P = d(1/v_S\text{-}1/v_P) = d(1/2.2 - 1/3.7) = d(0.184)$. Solving for d gives: $d = T/0.184 = 5.4\ T$. We approximate this as $\mathbf{d} = 5\ T$.

the rock blanket between it and us, the heat radiation from the core would quickly burn us to a crisp.

So much for curious facts--the real question for now is: how could we possibly know all this? The deepest we can drill is only a few miles. Nobody has ever gone to the core. Volcanoes don't come from regions that deep. How could we possibly know?

The interesting answer is that we know from watching signals from earthquakes. Thousands of these happen every year, and they are studied by earthquake detectors all around the Earth. The largest earthquakes send strong waves that travel down through the bulk of the Earth, and are detected on the opposite side.

An interesting aspect of the earthquakes is that **only the P waves pass through the core**. The S waves are all reflected! That is the wonderful clue. P waves are longitudinal "pressure" waves, and they travel through rock, air, or liquids. But S waves are transverse "shear" waves. Shear waves travel through solids, but they don't go through liquids or gases. That's because liquids and gases moving in the transverse direction can just slip past the rest of the liquid or gas; it doesn't exert much shear. So the fact that the P waves pass but the S waves don't gave one of the clues that there is a liquid core. Scientists also measured the speed at which the waves travel, and from this they can rule out gas and many kinds of liquids. They measure the density of the core from its contribution to the mass of the Earth, and they also see the magnetic field that the core creates. From all this, they were able to rule out every possible liquid except iron, although there could be liquid nickel mixed in with it.

We believe that the iron melted on the Earth when the Earth first formed. Most of the iron sank to the core, since it was denser than the other rock. The liquid iron is still in the core and it hasn't yet completely cooled off. The very center of the core, called the inner core, is under great pressure. Even though it too is hot, the inner core has been compressed into a solid. If the pressure of all the weight of the Earth were removed, it would turn into a liquid, or possibly into a gas.

Discussion question: how do we know the liquid core has a solid center? (Or rather, how did scientists figure that out?) For the answer, see the footnote.[8]

Bullwhips

In a bullwhip,[9] the thickness of the whip is tapered towards the end. When the whip is snapped, a wave begins to travel down the whip to the end. Because the end is thin, the velocity of the wave increases near the end. The

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[8] When a compressional wave hits the depth of the inner solid core it breaks up into two waves. From the behavior of these waves, we know that one of them is a shear wave. So although shear wave didn't travel through the outer core, shear waves are generated in the inner core. That means that the inner core must be made of a solid.

[9] If you don't know what a bullwhip is, then you might watch the opening scene in the movie *Indiana Jones and the Raiders of the Lost Ark* (1981) in which Indiana Jones uses a bullwhip to "whip" a gun out of the hand of a bad guy.

loud “crack” that you hear from the bullwhip is a sonic boom that occurs when the velocity of the wave exceeds the speed of sound.

Note this difference: in earthquakes and tsunamis, the added danger comes because the wave enters a region in which it slows. In the bullwhip, the crack comes because the wave speeds up.

Waves can cancel (or reinforce)

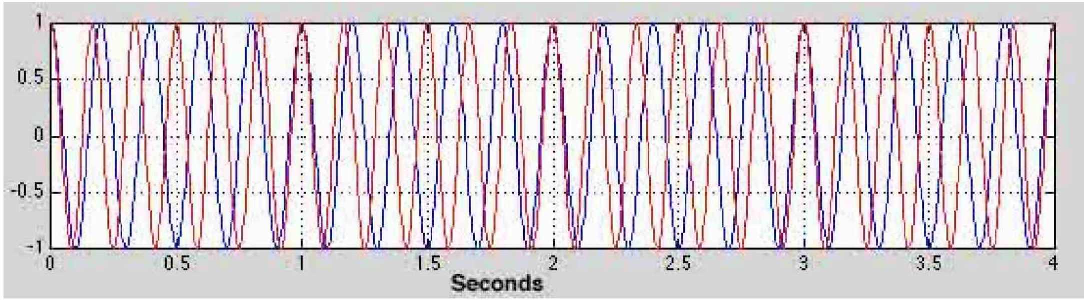
Suppose you are very unlucky, and are standing right in the middle of two earthquakes. One is to the north, and it takes you up, down, up, down, up, down, etc. The other earthquake arrives from the south, and it shakes you down, up, down, up, down, up, etc., exactly the opposite of the shaking of the first wave. What will happen? Will the up from one be canceled by the down of the other?

The answer is yes! If you are unlucky enough to be between two such waves, then try to be lucky enough to be at just the right place for them to cancel. You are depending on the fact that the two waves arrive with exactly opposite shakings.

Of course, if you were standing at a different location, the waves would arrive at different times, and they might not cancel. Suppose the first wave gave you up, down, up, down... and so did the second wave. Then the ups would arrive together, as well as the downs, and you would be shaken twice as much.

This circumstance is not as unlikely as you might think. Even if there is only one earthquake, parts of the wave can bend, and so you can be hit by the same earthquake but from two different directions. If you are lucky, the two waves will cancel, but a short distance away, they can add. This phenomenon was see in the 1989 Loma Prieta earthquake that shook Berkeley, Oakland, and San Francisco. There were buildings where one side was shaken badly (causing that side to fall down) and the other side of the building was undamaged. This was probably due to the arrival of the wave from two directions at once, and the cancellation of the wave at the lucky end of the building.

If two waves are traveling together in the same direction but have different wavelengths (or frequencies), then the same kind of cancellation can happen. Take a look at the two different waves shown in the plot on the next page, one in lighter in color and one darker. The curves show the amount that the ground moves up and down (in centimeters) at different times due to the light earthquake and the dark earthquake. Zero represents the original level. The dark earthquake shakes the ground upward (to 1 cm), and downward (to -1 cm). So does the light earthquake. So far, we have not considered the effects when added together.



First look at the darker wave. At zero seconds, it starts at the maximum value of 1. It oscillates down and up, and by the time it reaches 1 s it has gone through 5 cycles. (Verify this. Try not to be distracted by the lighter wave.) We say that the frequency of the dark wave is 5 cycles per second = 5 Hz.

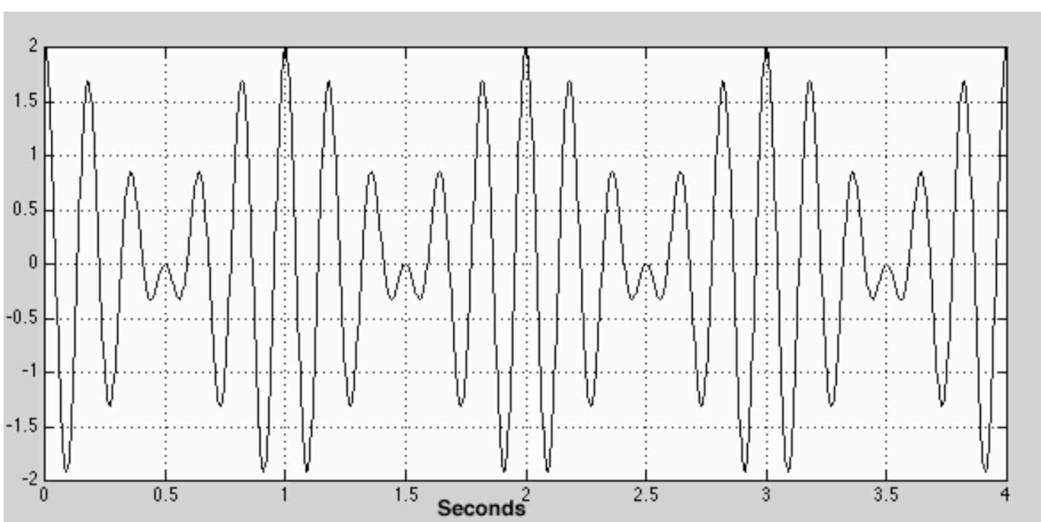
Now look at the light curve. In 1 s, it oscillates up and down 6 times. The frequency of the light wave is 6 Hz.

Suppose you are shaken by both waves at the same time. At time zero, you are shaken in the upward direction by both the dark and light waves; their effects add, and you will move up by 1 + 1 = 2 cm. Look at what happens at 0.5 s. The red wave is pushing you up by 1 cm, and the dark wave is pushing you down by 1 cm, so the two effects cancel, and at that instant you will be at level ground.

Note that there are also times when both waves are pushing you down. There's no place when they are both exactly at their minima, but they come pretty close at about 0.1 s. At this time both light and dark waves are down near -1 cm, so the sum effect will be to lower the ground by a total of 2 cm.

Beats

If we add the light and the dark waves, point by point, we get the oscillation shown below.



The curve is taller because it ranges between 2 and -2. The shaking is not as regular, because of the alternating reinforcement and cancellation. Try counting cycles, and see what you get.

You probably got a frequency of 6 Hz (that's what I got). But some of the cycles are much bigger than others. Mathematically, we would not try to characterize this oscillation by a single frequency; it is a superposition (sum) of two frequencies.

If you felt this combination of waves under you, would say that the shaking was modulated, with the biggest shaking taking place every 1 s (at 0, 1, 2, 3, 4, ...). These are called the **beats**. The beat frequency is given by this elegant equation:

$$f_{\mathrm{BEATS}} = f_1 - f_2$$

where f_1 and f_2 are the two frequencies that make up the signal (i.e. they are the frequencies of the light and dark waves). If the number comes out negative, ignore the sign; that's because beats look the same if they are upside down.

To demonstrate beats, you can listen to two tuning forks with slightly different frequencies. The demonstration that we use at Berkeley is described at www.mip.berkeley.edu/physics/B+35+20.html

For a very nice computer demonstration of how water waves can interfere, look at the UCLA site
http://ephysics.physics.ucla.edu/physlets/einterference.htm.
This site needs a fairly up-to-date browser with Java installed. You may already have that without knowing it, so it is worth trying. Move the red dots around, and then click on "calculate." Waves will come out of the two spots. These waves will add ("reinforce") at some locations, and cancel at others.

Music: notes and intervals

A musical note usually consists of sound waves that have one dominant frequency. The middle white key on a piano, known as middle C, has a frequency of 256 Hz (at least when the piano is tuned to the "Just scale"). The white keys are designated A, B, C, D, E, F, G, A, B...with the 8 different letters which repeat in cycles. They repeat because, to most people, 2 consecutive Cs sound similar. They are said to be an "octave" apart. In fact, when you go 1 octave (8 notes), the frequency is exactly doubled. So the C above middle C has a frequency of 512 Hz. The next C has a frequency of 1024 Hz. Normal human hearing is quite good up to 10,000 Hz, and some people can hear tones as high as 15 to 20,000 Hz.

If two notes are played at the same time, and their frequency differs by just a little bit, then you will hear beats. Suppose you have a tuning fork that you know has a frequency of 256 Hz. You play the C string on a guitar, and listen to it and the tuning fork together. If you hear 1 beat per second, then you know the guitar is mistuned by 1 Hz; it is either 255 Hz or 257 Hz. You adjust the tension on the string until the frequency of the beats gets lower and lower. When there no longer are beats, the string is "in tune."

The interval between the A note and the higher E note is called a "fifth" because there are five notes: A, B, C, D, E. Likewise, middle C and the higher G make a fifth: C, D, E, F, G.

A violin is tuned so that the fifth has 2 frequencies with a ratio of exactly 1.5. So, with the middle C tuned to 256 Hz, the G above middle C has a frequency of 379 Hz. This combination is also considered particularly pleasant, so many chords (combinations of notes played simultaneously, or in rapid sequence) contain this interval, as well as octaves.

Another pleasant interval is called the "third." C and E make a third. The ratio of notes for a perfect third is 1.25 = 5/4. The pleasant reaction of the sound is believed to be related to the fact that these frequencies have ratios equal to those of small, whole numbers.

A particularly unpleasant interval is the *tritone*, in which the frequencies have the ratio of 7/5. The tritone is used in music to make the listener temporarily uncomfortable, and so it is considered dissonant. It is also used in ambulance sirens to make a sound that you can't easily ignore.

Vibrations and the sense of sound

As I said, the middle C on a piano vibrates 256 times per second. The C below that is 128 Hz. The next lower C is 64 Hz, and the one below that is 32 Hz. That's pretty slow. If you can find a piano, play that note. Try singing it. Can you sense that your vocal cords are only vibrating 32 times per second? You almost feel that you can count the vibrations, but you perceive the tone as a tone, not as a collection of vibrations. If a light flickers at 32 times per second, you sense it as flickering, but your eye is more sensitive to the rapid changes than your ear. TV sets in Europe flicker at 50 Hz, and many people notice that. In the United States, TVs flicker at 60 Hz; most people do not perceive this! It is strange that the eye responds so differently to 50 Hz than to 60 Hz.

Ordinary house electricity oscillates 60 times per second, from positive to negative and back. Sometimes this causes a buzz in electronics, or in a faulty light bulb. The buzz is actually 120 times per second, since both the positive and the negative excursions of the current make sound. Do you remember hearing such a buzz? Can you hum the buzz, approximately? That is 120 Hz.

Remember the sound of the "light saber" in the Star Wars movies? That sound is 120 Hz. It sounds like a faulty fluorescent light bulb. In fact, it was made by picking up the buzz from electrical wires.

Noise-canceling earphones

Because sound is a wave, it can be cancelled just like the shaking of an earthquake. So some smart people have made earphones that have a built-in microphone on the outside. This microphone picks up noise, reverses it, and then puts it into the earphone speakers. If done correctly, the reversed sound exactly cancels the noise, and the wearer hears "the sound of silence." On top of this quiet, the electronics can put music into the earphones. Since the music does not reach the outside microphone, it is not cancelled.

I have a set of Bose noise-canceling earphones and I use them mostly on airplane flights. The result is that I can listen to high quality classical music, or to a typical airplane movie, and hear it as clearly as I would in a movie theater, without distracting noise.

There are even more expensive versions of noise-canceling earphones that are used by professional pilots and others who work in very noisy environments. It would be very nice to be able to cancel noise over a much larger region, e.g. in an entire room. However that is probably not possible, at least not from a single small speaker. The reason is that the wavelength of sound (see next section) is typically 1 m. If the noise is not coming from the same location as the speaker, then although the sound could be cancelled in one location, it would probably be reinforced in a different location. That is not a problem for earphones, since the entire earphone is so small. Noise cancellation for an entire room might be possible if the walls of the room were made out of loudspeakers, or if they otherwise could be caused to vibrate to cancel any noise that might otherwise pass through.

Wavelength of sound

Let's apply our wave equation to sound. Recall that the equation is:

$$v = f\,L$$

Let's use this equation to figure out the wavelength of sound for middle C on a piano. That has f = 256 Hz. You learned in Chapter 1 that the velocity of sound in air is about 330 m/s. So the wavelength is $L = v/f$ = 330/256 = 1.3 m.

Does that seem long to you? It is large compared to the typical size of a head, so the wave is moving your two ear drums together.

Suppose we go up by 3 octaves. That means the frequency is doubled 3 times, i.e. increased by a factor of 8. Since the sound velocity v is the same in the wave equation, that means that the wavelength will be reduced by a factor of 8, from 1.3 meters, to 0.16 meters = 16 cm. That's smaller than the distance between your ears. So for this frequency, the eardrums on the opposite sides of your head may be vibrating opposite to each other.

Doppler shift

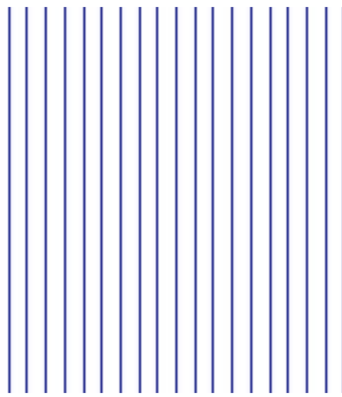
When an object is approaching you, you'll hear a higher frequency than the one they emit. That's because each time a crest is emitted, or a trough, the object is closer to you than it was for the previous cycle. So you hear them closer together. Likewise, if the object is moving away, you'll hear a lower frequency. This effect is called the Doppler shift, and it is extremely important in radar and in cosmology since it allows us to detect the velocity of very distant objects.

When a car or truck goes by, listen to the sound. I'm not sure how to describe it in words--something like "shhhhh–ooooo." (Sorry. That's the best I could come up with. Suggestions for better ways to write this would be appreciated.) But the important thing to note is that the pitch of the sound drops just as the car goes by (that's the change from the shhhhh to the ooooo). That's the Doppler shift.

The Doppler shift is seen in all waves, not just sound. The Doppler shift in light means that an object moving away from you has a lower frequency. In astronomy, this is referred to as the red shift. It was from the red shift that Edwin Powell Hubble 1889-1953) discovered that the Universe is expanding away from us.

Huygens's Principle --
why waves bend toward the slow side

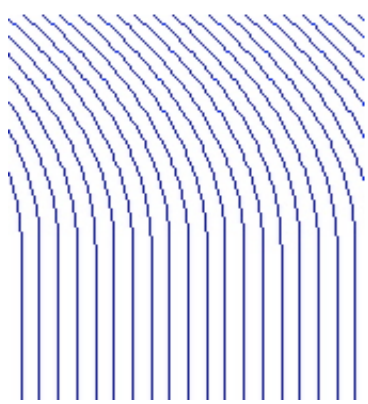
Imagine you are in an airplane, and you are watching waves on the ocean. Draw lines on the crests of the waves, i.e. on the highest points. Suppose the waves are moving to the right. The image will look like this:



Look carefully at this image. The lines are the crests, i.e. they are the high points of the waves. The waves are all moving towards the right. That means that if we had a movie, each crest (each line) would move towards the right. In between the lines are the low points of the water waves, called the troughs. They move too.

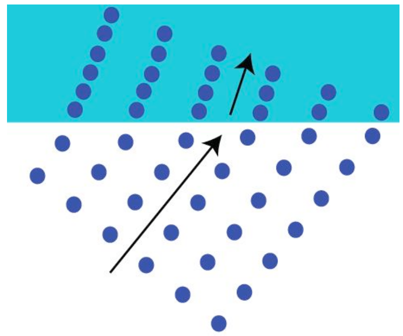
Recall that the distance between the crests is called the wavelength. In the figure, the wavelength is the separation of the lines.

Now imagine the waves moving to the right, but the ones near the top of the picture moving slower than the ones at the bottom. The lines would have to distort for this to be true. This is what it would look like:



The waves near the top are moving to the right, but slower than the ones near the bottom. They will arrive at the right edge later. Notice how the slowing tends to bend their direction. But also notice that the waves near the top are becoming diagonal. The crests are no longer straight up and down. The direction of the wave is perpendicular to the crest. So the wave is no longer moving from left to right, but is also moving slightly upward. The direction has changed towards the side that has slower velocity.

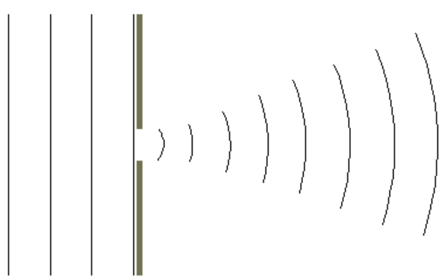
The same thing would happen with a marching band (assuming that adjacent band members held hands), seen from above, if the field near the top was muddy and the members marched slower than the ones near the bottom. This is illustrated in the figure below.



Note how the direction of the marching band (the arrows) changes once the band enters the muddy field – presuming that they try to stay lined up with each other. For waves, they do stay lined up, because each wave is generating the next one. That is a big abstraction, but many people find the above diagram helpful anyway. This method of explaining wave direction change is called "Huygens principle".

Spreading of waves

Any wave, when passing through an opening, spreads. If not for such spreading, we usually would not hear people shout when they talk from behind a corner. The figure below left shows a wave (coming from the left) going through a hole and spreading out. On the right is a photo of waves passing through a gap in a floating log (taken by Michael Leitch).



There is a simple formula for this spreading of waves. The only thing you need to know is the wavelength of the wave L and the diameter of the opening D. Then the size S of the wave when it goes a distance R will be given by the approximate formula

$$S = \frac{L}{D} R$$

You don't need to learn this formula, but it will be useful for us to calculate wave spreading. It becomes very important for light, because it limits the ability of telescopes to "resolve" objects. As we will show in the next chapter, this spreading is what prevents spy satellites from being able to read license plates.

This spreading equation is true for all kinds of waves, including sound waves and earthquake waves. The same equation works for them all. Let's take sound as an example. We showed above that for the tone of middle C, the wavelength is L = 1.3 meters. Suppose this sound passes through a doorway that is 1.3 meters in diameter. If not for the spreading, the wave would be only 1.3 meters in diameter even after it went 10 meters past the door. But from the equation, there will be spreading. The amount of spreading will be large:

$$\begin{aligned} S &= \frac{L}{D} R \\ &= \frac{1.3}{1.3} 10 \\ &= 10 \text{ meters} \end{aligned}$$

The spreading is so great that you can hear a person on the other side of the door even if you can't see him. The spreading of light will be much less, because L will be much smaller. We'll talk about the spreading of light in the next chapter.

Chapter Review

Waves travel in many materials, such as water, air, rock, and steel. Even though the material only shakes and none of the molecules move very far, the wave moves and carries energy over long distances. Waves are longitudinal when the direction of vibration is along the direction of the wave. Longitudinal waves include sound waves and the P earthquake wave. Waves can also be transverse. This means that the shaking is perpendicular to the direction of motion. An example is a wave on a rope. Water waves are both transverse and longitudinal. Light waves travel in a vacuum or in a material such as glass. They consist of a shaking electric and magnetic field. Light waves are transverse. Electrons and other particles are actually waves too, but they are so short ("wave packets") that this was not discovered until the 20^{th} century. The fact that particles are waves is called the theory of quantum mechanics.

If a wave repeats, then the number of repeats per second is called the frequency. For sound, frequency is the tone, i.e. high pitch or low pitch means high frequency or low frequency. For light, frequency is color. Blue is high frequency and red is low frequency. The wavelength is the distance between crests of the wave.

The velocity of the wave depends on the material it is passing through. Sound travels about 1 mi/5 s through air, but 1 mi/s in water, and even faster in rock and steel. Light travels at 1 ft every billionth of a second, i.e. 1 ft per typical computer cycle. That is 186,000 mi/s.

The speed of sound depends on the temperature of the air. In hot air, sound travels faster. If sound is traveling horizontally, but the air above or below has a different temperature, then the direction of the sound will bend towards the side that is slower. This phenomenon causes sound to get trapped beneath the ocean, and is exploited by whales to send sounds thousands of miles. It also was used by the military for sofar (locating downed pilots) and for SOSUS (to locate submarines). If four different microphones can pick up the same sound, then the source of the sound can be located. The same principle is used using radio waves for GPS.

A sound channel in the atmosphere is created because of the high altitude heating caused by the ozone layer. Project Mogul took advantage of the sound channel in the atmosphere. It was designed to detect Soviet nuclear tests. When the flying microphone disks crashed near Roswell, New Mexico in 1947, stories began to spread about flying saucers.

When the ground is cool, sound bends downward, and that lets us hear distant sounds. When the ground is warm, sound bends upward, and we do not hear distant sounds.

The velocity of sound waves does not depend on their frequency or wavelength. If it did, it would be hard to understand speech from someone standing far away. But the velocity of water waves does depend on the frequency and wavelength. Long wavelength water waves travel faster than short wavelength ones. Very long wavelength water waves, usually triggered by earthquakes, are called tsunamis or tidal waves.

Earthquakes begin when a fault ruptures at the epicenter, but they then travel as waves to distant places. The Richter scale gives a rough idea of the energy released. One point in the Richter scale is about a factor of 10 to 30 in energy released. The P wave is a compressional wave that travels fastest. Next comes the S wave (transverse), and finally the L wave. The time between the P and the S wave can be used to tell the distance to the epicenter. The fact that S waves do not travel through the center of the Earth, enables us to deduce that there is liquid there, probably (from the velocity we measure) liquid iron.

Waves can cancel, and that gives rise to beats (in music) and to strange effects, such as buildings that feel no shaking because of the fact that two canceling earthquake waves approached the building from different directions.

Essay questions

The eye is a complicated feature of the human body. How does it work? Discuss the relevant physics. In your essay, include answers to the following questions: What does it mean to be nearsighted or farsighted? How does aging play into this process? How does the eye see colors? What does it mean to be colorblind?

Everybody knows that water waves are waves, but in fact, there are many different kinds of waves in the world that are not obviously waves. Give examples of as many such phenomena as possible. For each, site evidence that you might present to a skeptic to show that they really are waves.

Sound doesn’t always travel in straight lines. The bending of its direction as it travels gives rise to many interesting phenomena. Give examples, and include details that would help a new student understand them.

Waves have a peculiar property: they can cancel. Give examples of cancellation for sound, light, water, and earthquakes. Explain why cancellation is so difficult to observe for light.

Most people have never heard of a “sound channel”. Give two examples of sound channels. Describe how the velocity of sound varies with location, and how this affects the direction of the waves. Give examples of the practical use of these channels.

Discuss the noticeable and/or important effects that arise from the different velocities of waves as they travel though different parts of the same material.

Discuss the noticeable and/or important effects that arise from:
(1) the cancellation and reinforcing of waves, or
(2) the different velocities of waves as they travel though different parts of the same material

Water waves and sound waves are both waves, despite the fact that they appear to be dissimilar to most people. Describe the way that they are both waves, properties they both share. What properties of sound make it clear that sound is really a wave?

Everyone knows that an earthquake is the shaking of the ground. Describe the ways in which it acts like a wave. How can the S and P waves be used to determine the location of the epicenter and the nature of the interior of the Earth?

Describe the properties of sound underneath the ocean surface. Describe how sound moves, and the implications of this for life (wild and human) under the water.

Describe how sound travels in air near the surface of the Earth. How does it depend on time of day and weather conditions? What interesting phenomena can an observant person notice?

According to the text, what were the “flying disks” that crashed near Roswell, New Mexico? Describe the formerly classified program that they were to be used for. Make sure to include all the relevant physics.

The sofar disks used by the Navy had remarkable properties. Describe how they work, and how they were intended to be used. Make sure to include all the relevant physics.

Multiple-choice questions

Beats measure:
( ) frequency
( ) the difference between two frequencies
( ) loudness
( ) the presence of noise

Waves tend to bend in the direction that
( ) wave velocity is slower
( ) wave velocity is faster
( ) is upward
( ) is downward

The fastest earthquake wave is the
( ) L wave
( ) S wave
( ) P wave
( ) they all travel at the same speed

The slowest earthquake wave is the
( ) L wave
( ) P wave
( ) S wave
( ) they all travel at the same speed

The spreading of a wave as it passes through an opening is called:
( ) dispersion
( ) diffraction
( ) refraction
( ) inversion

An “octave” refers to two frequencies which differ by a factor of:
( ) 1.5
( ) 2
( ) 8
( ) sqrt(2)

When two different waves pass through an opening of the same size,
which one will spread more?
( ) smaller wavelength
( ) larger wavelength
( ) higher frequency
( ) lower frequency

The fastest sound wave is:
( ) low frequency
( ) middle frequency (voice)
( ) high frequency
( ) they all travel at the same speed

You can measure the distance to the epicenter by measuring
( ) The amplitude of the P wave
( ) The amplitude of the S wave
( ) The frequency of the L wave
( ) The time between the P and S waves

Sound travels fastest in:
( ) air
( ) water
( ) rock
( ) vacuum

When an opening gets smaller, a wave that passes through it:
( ) spreads more
( ) spreads less
( ) stays the same
( ) changes its wavelength.

The very center of the earth is:
( ) pure rock
( ) liquid rock
( ) liquid iron
( ) solid iron

Which of the following statements about earthquakes is true?
( ) S waves are fastest and cause the most destruction.
( ) P waves are fastest and L waves cause the most destruction.
( ) L waves are slowest and P waves cause the most destruction.
( ) P waves are fastest and cause the most destruction.

Which kind of earthquake wave is purely longitudinal?
( ) L wave
( ) P wave
( ) S wave
( ) they are all longitudinal

The L wave is often the most damaging because
( ) it stays on the surface, so doesn’t spread out very much
( ) it moves slowest, so it has the greatest energy per mile
( ) the S and P waves carry too little total energy
( ) It arrives first, before people have a chance to take cover

An earthquake waves does its worst damage when it reaches an area that
( ) slows it down
( ) increases its frequency
( ) decreases its frequency
( ) adds additional energy

Land fill is dangerous because:
( ) the frequency of an earthquake increases
( ) the wavelength of an earthquake increases
( ) they tend to focus earthquake energy
( ) the amplitude of the earthquake increases

When there is an atmospheric “inversion”, then sound tends to:
( ) become focused
( ) bend upwards
( ) bend downwards
( ) become absorbed

The ocean sound channel:
( ) is very quiet
( ) is very noisy
( ) is radioactive
( ) focuses earthquakes

The same note is heard on two pianos. Beats are heard once per second.
From this we deduce:
- ( ) at least one of the pianos is out of tune (the notes are at the wrong frequency)
- ( ) both pianos are out of tune
- ( ) the pianos have been accurately tuned
- ( ) the pianos will sound especially pleasant if played together

We know that the inner part of the Earth is liquid because:
- ( ) No S waves move across it
- ( ) We can detect the flow of material from the emitted sound
- ( ) At such great pressures, everything becomes liquid
- ( ) neutrinos pass through it and show the pattern

A Richter magnitude 9 earthquake, compared to a Richter 8 earthquake
- ( ) has twice the energy
- ( ) has 10 to 30 times the energy
- ( ) has velocity 2 x faster
- ( ) has velocity 10 to 30 x faster

You feel the tremors of an earthquake. 10 seconds later you feel another, stronger shaking. The distance to the epicenter is about:
- ( ) 2 miles
- ( ) 5 miles
- ( ) 10 miles
- ( ) 50 miles

If we double the frequency of sound, the wavelength is
- ( ) doubled
- ( ) halved
- ( ) unchanged
- ( ) quadrupled

Beats demonstrate that
- ( ) sound is a wave
- ( ) sounds bends
- ( ) sound bounces
- ( ) sound spreads

The velocity of sound is approximately:
- ( ) 1000 ft per second
- ( ) 1 mile per second
- ( ) 5 miles per second
- ( ) 186,284 miles per second

The speed of sound in air
- ( ) is always the same
- ( ) increases if you shout louder
- ( ) depends on frequency
- ( ) increases as air temperature increases

Sound waves are:
- ( ) transverse
- ( ) compressional (longitudinal)
- ( ) a combination of transverse and compressional

During a typical day, sound emitted near the ground tends to bend:
- ( ) upwards, towards the sky
- ( ) downward, towards the ground
- ( ) not at all; it goes straight

You are more likely to hear distant sounds when
- ( ) the air near the ground is warm and the air above it is cool
- ( ) the air near the ground is cool and the air above it is also cool
- ( ) the air near the ground is warm and the air above it is cool
- ( ) the air near the ground is cool and the air above it is warm

Because of evaporation, the air above the surface of a lake becomes cool. Sound in the air above the lake will tend to:
- ( ) bend upward away from the surface
- ( ) bend downward towards the surface
- ( ) go in a straight line parallel to the surface
- ( ) go alternatively up and down

Sound tends to bend towards
- ( ) colder air
- ( ) warmer air
- ( ) denser air
- ( ) less dense air

To have a sound channel, there must be
- ( ) a minimum in the velocity of sound
- ( ) a maximum in the velocity of sound
- ( ) a decrease of the velocity with depth
- ( ) an increase of the velocity with depth

SOFAR took advantage of
- ( ) the sound channel in the ocean
- ( ) the sound channel in the atmosphere
- ( ) the magnetic field of the earth
- ( ) the uncertainty principle

The sound channel in the ocean carries sound a long distance because

( ) the ocean doesn’t absorb sound at that level
( ) whales listen to the sound and sing it over, increasing its volume
( ) the pressure of the ocean at that depth makes sound louder
( ) the sound doesn’t spread out in the up or down directions

As you travel deeper into the ocean, the water temperature T:

( ) decreases with depth
( ) increases with depth
( ) does not change with depth
( ) first gets colder, and then gets warmer

A pianist plays two keys: middle C, and the C above middle C (i.e. an octave higher). The speed of sound for the higher frequency, compared to that for the lower frequency, is (careful: possibly a trick question):

( ) the same
( ) 2 x faster
( ) 2 x slower
( ) sqrt(2) faster

As you move to a higher altitude, the temperature of the air

( ) first gets cooler, then warmer
( ) stays constant, then gets cooler
( ) first gets warmer, then cooler

The atmospheric sound channel would not exist, if not for:

( ) thunderstorms
( ) carbon dioxide
( ) ultraviolet light
( ) infrared light

The ozone layer is created by:

( ) carbon dioxide
( ) lightning
( ) sunlight
( ) chlorofluorocarbons

SOSUS refers to

( ) a method of rescuing pilots designed during WWII
( ) a project to detect nuclear explosions
( ) a system for detecting submarines
( ) a system using many artificial Earth satellites

Which of the following was true about project Mogul?

( ) It was concerned with the atmosphere
( ) It resulted in the first nuclear bomb
( ) It led to the discovery of nuclear fission
( ) It involved the invention of integrated circuits

According to this text, the “Flying Disks” that crashed near Roswell were:

( ) advanced space vehicles
( ) nuclear weapons
( ) microphones
( ) U-2 airplanes

An electromagnetic wave is a

( ) longitudinal wave
( ) transverse wave
( ) both a longitudinal and transversal wave
( ) none of the above

The colors of a soap bubble indicate that

( ) light is a wave
( ) light is a particle
( ) light travels slower in soap
( ) light travels faster in soap

The mirage of water on a road comes from

( ) light bending downward
( ) light bending upward
( ) blue light bending more than red
( ) red bending more than blue

Water waves are

( ) pure transverse waves
( ) pure longitudinal waves
( ) both transverse and longitudinal
( ) compressional

Very long wavelength water waves

( ) travel slower than short ones
( ) travel faster than short ones
( ) travel the same speed as short ones
( ) travel faster if they have high amplitude, and slower if they have low amplitude

Whales and fiber optics both make use of what principle?

( ) Huygens’s
( ) Heisenberg’s
( ) Moore’s
( ) Curie’s

When an earthquake at sea starts a tsunami or tidal wave, the initial height is relatively small. What accounts for the towering wave that breaks near the shore?

( ) the wave builds up energy as it moves
( ) the wavelength increases
( ) the depth increases
( ) the wave moves faster
( ) the wave moves slower
( ) its appetite for destruction is piqued

A water wave has a wavelength of 10 meters, and a frequency of 2 cycles/sec.
It's velocity is:

( ) 5 meters per second
( ) 10 meters per second
( ) 20 meters per second
( ) 50 meters per second

The Global Positioning System (GPS) works when you receive radio waves from at least:

( ) one satellite
( ) three satellites
( ) seven satellites
( ) millions of satellites

GPS works by:

( ) sending signal to satellites that then radio back the location
( ) receiving signals and calculating the position
( ) detecting the position by using radar reflections
( ) measuring sound

Thunderclouds tend to rise until

( ) they rain out all their water
( ) they reach air that is colder than they are
( ) they hit the carbon-dioxide layer
( ) they reach air that is warmer than they are