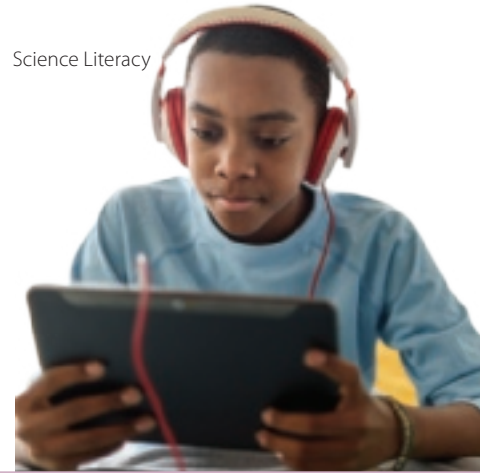


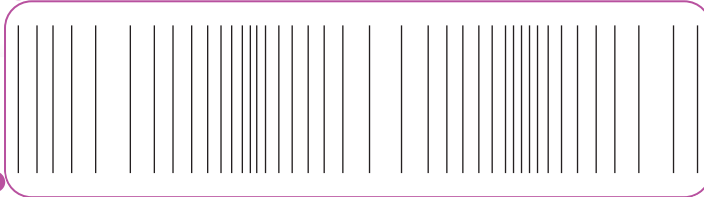
# Sound Waves:

## How can a sound make something move?



Science Literacy Student Reader

Wavelength models



Vibration



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# Sound Waves

Science Literacy Student Reader



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# Sound Waves

## Table of Contents

Preface	<b>Put Yourself in This Scene</b> .....	2
Collection 1	<b>Musical Instruments</b> .....	6
Collection 2	<b>Sounds in Nature</b> .....	16
Collection 3	<b>Sound and Media</b> .....	26
Collection 4	<b>Compression Waves</b> .....	36
Collection 5	<b>Air, Wind, and Sound</b> .....	46
	<b>Glossary</b> .....	56
	<b>Key Sources</b> .....	57



# Put Yourself in This Scene

On your way home from school, your phone buzzes in your pocket. You've gotten a social media notification. It's a post shared by your good friend. She has added her own comment at the top of the post she's shared. The picture is a modified photo of the ocean just off the shore of your town.



Intrigued, you tap to read more.

You read on:



**Rebecca Miles**



The proposed Mermaid Shoals Wind Farm will comprise 28 wind turbines with rotors that will span several hundred feet. The towers will be anchored to the shallow seafloor of the shoals, which has been treasured fishing ground for our local small-boat squid fishers for generations. Above the waves, the massive blades will slice through the air and kill migratory seabirds by the thousands. The noise from these blades will be a major nuisance, and the blades will also produce pressure waves that have been connected to frequent headaches, fatigue, and even depression and insomnia. The process of anchoring these structures so they do not topple over during storms will involve dredging thousands of tons of sand and rock, and tearing up the habitat of countless marine organisms including sponges, seagrasses, lobsters, crabs, and fishes. The noise from the construction of these monstrous turbines will disrupt the communications and migrations of marine mammals such as whales and dolphins. Running the heavy electrical cable from these turbines to the shore could spell further electromagnetic disturbance in this natural habitat. Moreover, the output of these turbines will be enough to power maybe one thousand homes—homes whose values will decline due to the unsightly turbines. Vote “no” on this project at the next town meeting!



*Well, that does sound pretty bad!* You are going to talk to your parents tonight at dinner to ask them if they plan to oppose this project. You care about fighting climate change by reducing our dependence on fossil fuels, but this particular project just seems to have too many downsides.

A moment later, the same app sends you another notification. Another friend has shared a post on this same issue. His comment says:



**Andre Green**



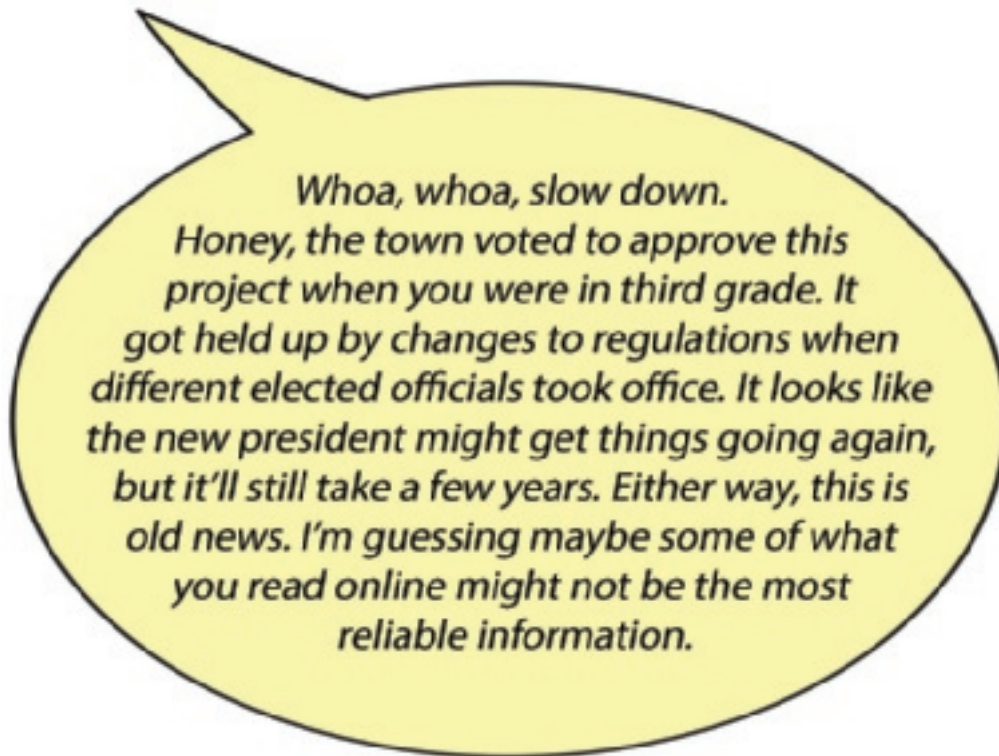
**This project will help our community and our planet!**

Despite what you may have heard from the well-financed opponents of the Mermaid Shoals Wind Farm, most of whom are just concerned with how the turbines will affect the views from their summer homes, this project is a net positive for our community and the whole planet. The turbines will be so far from shore that they will barely be visible to us except on the clearest of days. The only way to hear any noise from them will be to take a boat to the shoals, record the sound, and then speed up the playback so the low frequencies emitted by the turbines can actually be audible to human ears. Any talk of ill health effects is based on junk science and questionable reports from people who are outspoken opponents of the project. The overall impact on the local shallow-water habitats and wildlife, including migratory birds and marine mammals, will be negligible compared to what the fossil fuel industry has done and continues to inflict. For example, seismic surveys conducted in the very same waters to find deposits of oil or natural gas have been blamed for mass stranding events that killed hundreds of pilot whales, and ship strikes between oil tankers and North Atlantic right whales have held this endangered species' population to fewer than 350. There is simply no comparison between the costs and benefits of this renewable energy project and the carnage of the nonrenewable energy industry. Vote "yes" to Mermaid Shoals Wind Farm!



Now you aren't sure what to believe. You decide to discuss both sides of the issue at dinner.

As you swipe through the different posts on your phone to summarize the key points you have absorbed, your mom cuts you off:



What you read was on an app you use all the time, and the posts were from your friends. You want to believe them both. But maybe they are just sharing stuff that they came across from somewhere else, too. Do your friends know how to tell fake news from real? Or real science from junk science? Do you?

That's what this book is about—scientific literacy, which means knowing how to think about science topics that you read or hear about. Our world has 24-7 news, social media, and too many websites to count. The amount of information we have to sort through is overwhelming, and all the information is not reliable. In the internet age, sources of information are often obscure or not trustworthy. It is good to process information with a healthy degree of skepticism.

We will make our way back to this wind turbine topic by the end of the book. Along the way, the series of reading selections and the writing exercises that go with them will help you flex your mental muscles and sharpen your science literacy skills. The ability to read about science, understand the information, and tell truth from fallacy or misrepresentation is really important. Science literacy helps you as an individual and as a consumer, and it shapes the ways you affect the community in which you live.

# Music Makers

Different families of musical instruments produce their signature sounds in different ways, but the product of every musical instrument is a sound wave, which travels from the instrument, through the air, to the ears of listeners.

## Strings

**Stringed instruments** involve strings stretched taut between two points along a neck or across a soundboard. Often one end of the neck is attached to some kind of resonant body that amplifies the sounds produced by the strings. Plucking or rubbing a string sets it in motion. That is the beginning of its **vibration**. Each string is tuned to a specific pitch.

On many stringed instruments, the strings can be pressed against a fingerboard at specific points that correspond to specific notes. This pressing action shortens the part of the string that vibrates. A narrow, taut string will have a higher pitch. Shortening the effective length of that string will produce an even higher pitch. A looser, thicker string will have a lower pitch, but the pitch can be made higher by pushing the string against the fret somewhere along the fingerboard.



## Vocabulary

**vibration, n.** movement of an object or material back and forth past its starting position

## Percussion



**Percussion instruments** are played by striking surfaces. Direct contact between two materials sends sound vibrations into the surrounding air. This family of instruments includes objects as simple as two pieces of wood that are tapped against each other. The more complex xylophone consists of dozens of wooden bars that produce specific pitches when struck with a mallet.

The tones of percussion sounds vary with the materials and structures of the instruments. For example, a large bass drum produces a deeper, lower sound made of low-frequency sound waves. A smaller drum with a very tight head produces higher frequencies and thus higher pitches—more treble than bass. Tightening the head of a drum raises the pitch. Some drums emit different sounds by pairing other materials with one of the drum's heads. A snare drum, for example, has metal snares (coiled wires) across the skin on the underside of the drum. When the top head is struck, vibrations move to the lower skin and rattle the snares.

Some percussion instruments, such as most cymbals, emit complex sounds made of multiple frequencies, meaning there isn't a specific pitch that your ears can pick out. Others, such as steel drums, can produce definite notes and be used to play melodies. Because so many percussion instruments don't produce definite notes, though, most are used to provide the rhythm for songs.

## Which Is It?

**A Hybrid** The piano has strings, but is it a stringed instrument? Yes and no. Strings are stretched across a heavy metal frame inside a large wooden body. But the process of playing the strings is like percussion. The player presses down on keys on the keyboard, and then, internally, levers with felt-covered hammers swing into action and strike the metal strings.



**Wind instruments** produce sound by forcing air through openings and cavities and across surfaces of different sizes, shapes, and materials. The air movement originates from the mouth of the musician.

## Woodwinds

**Woodwind instruments'** sounds begin with the player blowing air through or across a mouthpiece. Some mouthpieces are cylinders with an opening that the player blows air across, like when you make a sound by blowing air across the opening of a glass bottle. Some of the air flows into the instrument. Flutes work like this. Other woodwind instrument mouthpieces have wooden reeds, and the flow of air across the reeds produces vibrations of a high pitch. Saxophones, bassoons, clarinets, and oboes are all reed woodwind instruments.

The longer or larger the instrument, the lower its range of sounds. For example, a baritone saxophone is larger than an alto sax, so it produces lower pitches.

Holes along the length of a woodwind instrument can be opened or closed by the player's fingers. In general, closing more holes makes the pitch lower. This is because the volume of vibrating air gets larger if more of the instrument's holes are closed. More open holes make the pitch higher. The amount of vibration of the air in the instrument depends on how the sound waves are packed together in the small space, and that affects the pitch of the sound.



## Brass

The **brass instruments** include the trumpet, coronet, bugle, French horn, tuba, and trombone. Some of these instruments are actually made of brass, but other metals can be used as well. What separates brass instruments from the woodwinds is the way the player's lips can be adjusted to affect the pitch. The player's lips fit into the cup-shaped mouthpiece. Forcing air through the tightened lips produces buzz-like vibrations. These vibrations travel into the instrument, and the player manipulates keys or other components to change the pitch of the sound.

More than in the woodwinds, brass instruments' sounds also come out of the large opening at the far end, called the bell. This allows for different objects to be put into the bell to mute or alter the tone. The trombone is unique in that its shape and internal volume are adjusted by moving a slide in and out. The more the slide is extended, the longer the internal distance inside the instrument for air to travel and the lower the pitch.



# Anatomy

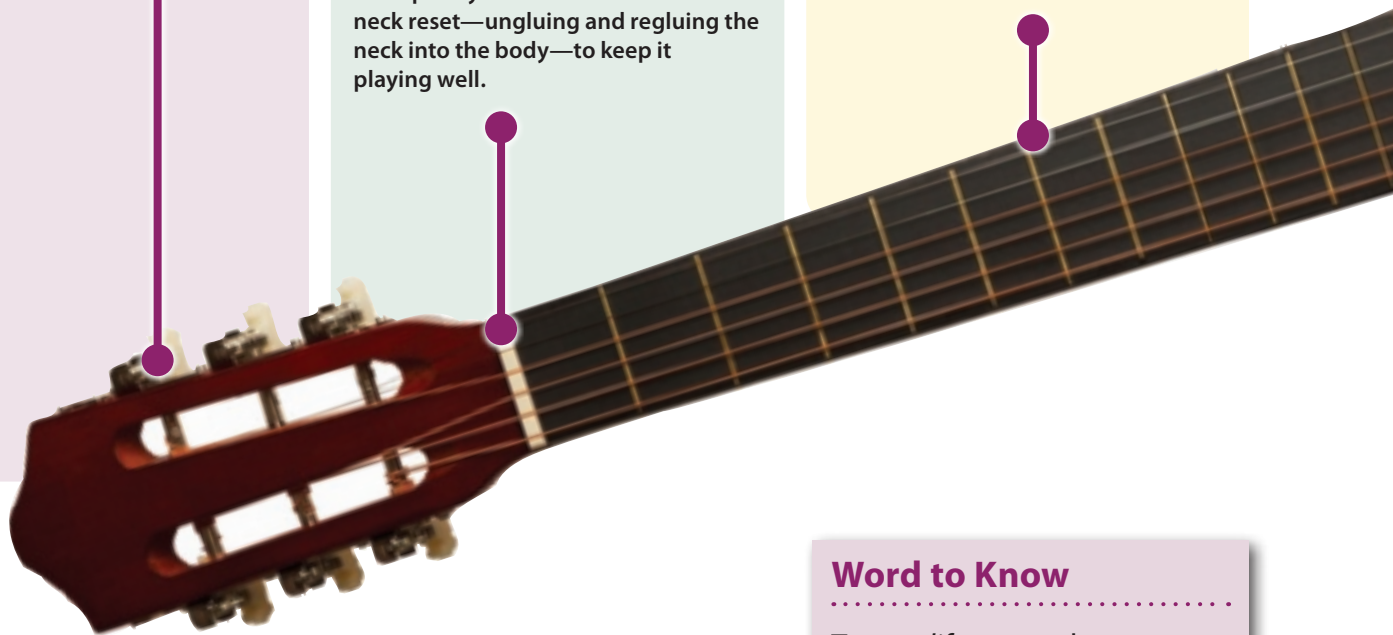
## of an Acoustic Guitar

The builders of stringed instruments, called luthiers, use a variety of techniques, shapes, tools, and materials to produce stringed instruments as large as the stand-up bass and as tiny as the ukulele. There are many different variables that affect the different properties of the sounds produced by stringed instruments.

On the far end of the neck, the ends of the strings are wound around tuning pegs, which have keys for our fingers to adjust the string tension. These tuners are found on the headstock.

Where the headstock bends and narrows into the neck is a bridge-like piece called the nut. The nut, often made of bone, has slots cut into it to hold the strings in place and space them out across the width of the fingerboard. The tension of the strings against the nut transmits vibrations through the neck, similar to the saddle in the bridge. Over time, string tension can warp the neck or pull the whole neck away from the body, so it is normal for a stringed instrument to need plenty of care and the occasional neck reset—ungluing and regluing the neck into the body—to keep it playing well.

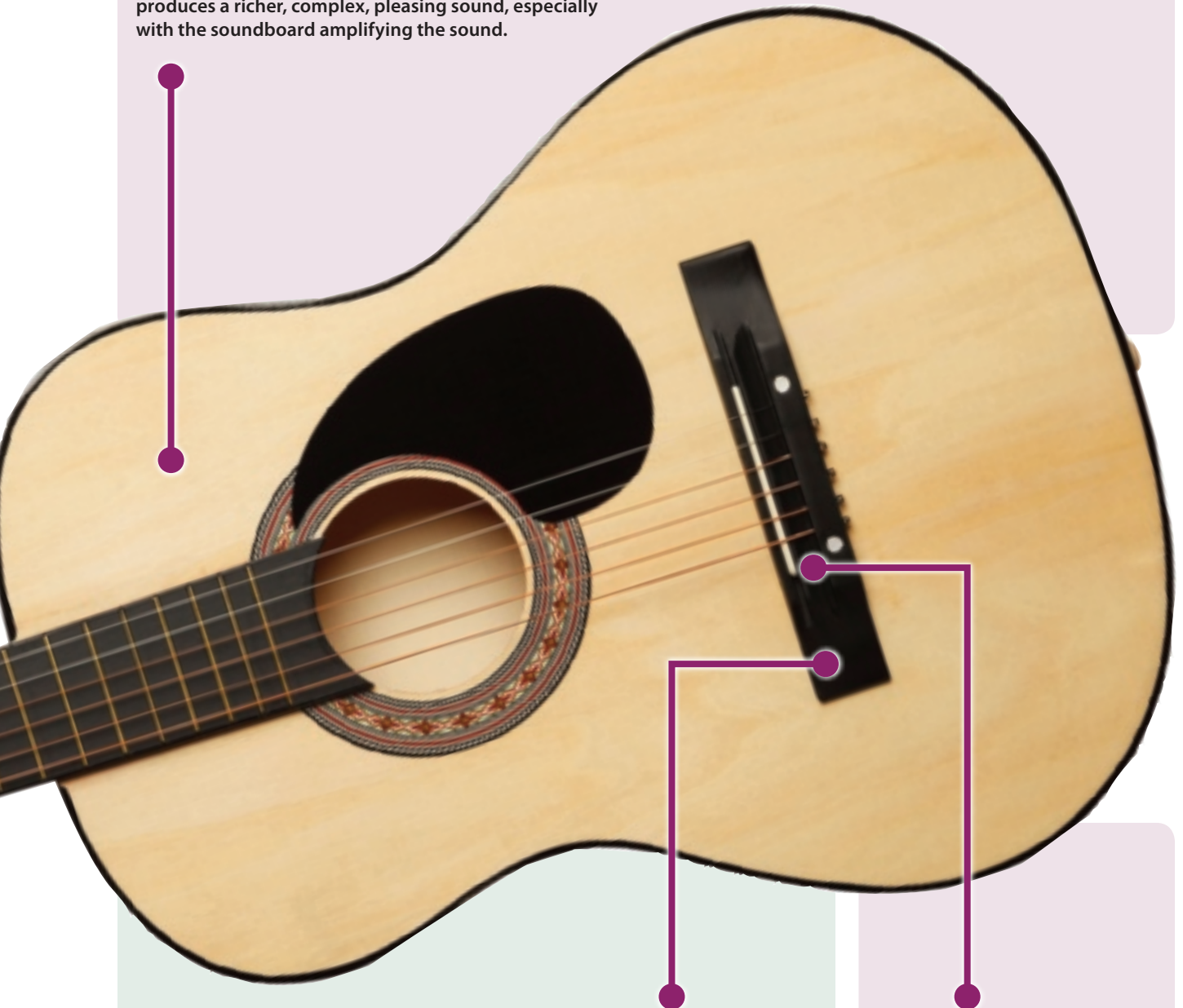
Each string has an effective length that runs from the saddle to the nut. The length, thickness, and tension of the string means the string will have a specific pitch when played. A player can also press strings against the fingerboard on the top face of the neck. This shortens the effective lengths of the strings and increases the pitches they produce. Different combinations of finger placements produce combinations of notes known as chords.



### Word to Know

To *amplify* a sound means to make it louder.

Many luthiers would argue that the most important piece of wood in a stringed instrument is the top, also known as the soundboard. This is the part of a guitar, ukulele, cello, or violin that is connected to one end of the strings and emits most of the sound heard in the air. Without the soundboard and the body of the instrument, sounds from stringed instruments would be relatively muted. The soundboard, often made of a tone wood such as spruce or cedar, helps amplify and project sounds outward, and it also adds characteristics to the sound. The primary tone is based on the frequency of the vibrating string, but that sound is often joined by a tone one octave higher, called a harmonic. The combination of different tones in harmony with each other produces a richer, complex, pleasing sound, especially with the soundboard amplifying the sound.



To anchor the strings to the soundboard, most stringed instruments have a connecting piece called a bridge. The bridge gets its name because it spans the strings and body and transmits vibrations to the soundboard. The bridge must be hard and durable so that vibrating strings do not cut too deeply into it over time and the bridge will not bend or warp. Hard, dense woods such as ebony and rosewood are popular for use as acoustic guitar bridges. For violins, maple is a favorite. A special glue connects the bridge to the soundboard of guitars.

Within the bridge there is often a slender piece of bone called a saddle. The strings run over the saddle and down into the bridge at a sharp angle. On violins and ukuleles, the string tension keeps the bridge in place.

## Analysis of Resonance of Sitka Spruce (*Picea sitchensis*) from Graham Island, British Columbia

### Introduction

The properties of woods used in musical instruments have a significant impact on the sounds that can be produced. Pitches are a function of frequency, and frequency is affected by the size, density, and elasticity of the wood. In stringed instruments, vibrations from strings are directed into the wood of the soundboard and other components, causing the wood to vibrate and intensify the amplitude of the sound. This is resonance. The soundboard's shape, the wood's natural frequency, and the condition of the surface of the wood further shape the sound, without changing the pitches produced by the strings.

Historically, spruce has been used as a resonant tonewood in stringed instruments, specifically for the tops, or soundboards, of acoustic guitars. Spruce has a high modulus of elasticity (MOE) in relation to its density. A tonewood's ability to resonate (ATR) is often associated with narrow growth rings, particularly from old trees (>130 years) in the case of Sitka spruce.

### Objective

This study examines the resonance of Sitka spruce grown on Graham Island, British Columbia, Canada, to determine if assumptions about the superiority of tight-grained, old spruce are based on measurable values.

### Background

Sitka spruce, *Picea sitchensis*, is a coniferous tree that can attain heights of 70 meters (230 feet) and widths of 2 meters (6.5 feet) at the trunk. It thrives along the coast of British Columbia from sea level up to 700 meters (2,300 feet), particularly near flood plains of rivers. Rich soil, mild temperatures, and plentiful rainfall allow for rapid growth, resulting in wide growth rings and coarse-grain boards cut from the trunks of these trees. Colder temperatures and less rainfall have yielded Sitka spruce trees with narrower growth rings and fine-grain boards. Historically, fine-grain boards have been most prized by luthiers and the tonewood industry.

### Words to Know

*Frequency* refers to how fast a material is vibrating.

In science, *density* is the proportional relationship between mass and volume. It's a way of quantifying how much matter is packed into a known amount of space.

*Elasticity* is a measure of how much something can be stretched or bent without breaking and then snap back into its original shape.

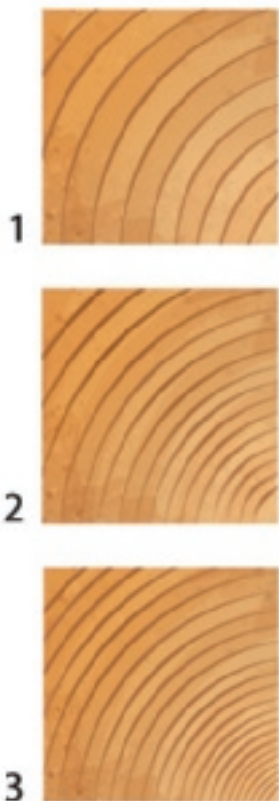
A material's *modulus of elasticity* is a quantity that measures how resistant the material is to temporarily deforming under stress.



## Methods

In this study we sampled Sitka spruce trees that were 200 to 600 years old from a forest that had a variety of growth rates. We categorized the trees and the samples cut from them as follows:

- 1) coarse-grain (5 to 8 growth rings per inch)
- 2) medium-grain (10 to 15 growth rings per inch)
- 3) fine-grain (about 20 growth rings per inch)



To measure the modulus of elasticity (MOE) of different trees, we cut samples that were

### Dig into Data

In this study, different samples of wood were cut and prepared in a consistent way so that three variables could be measured:

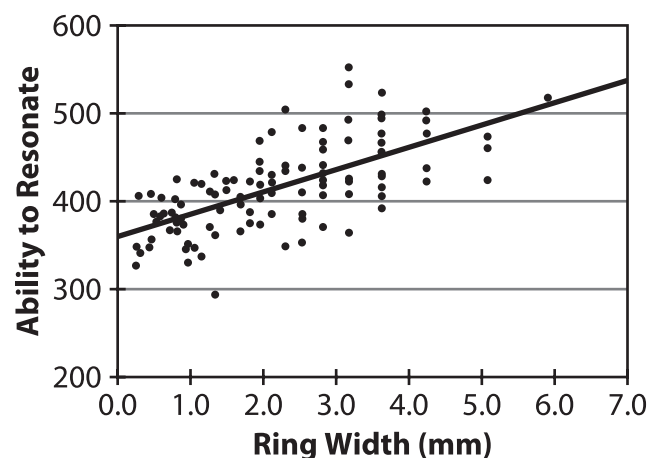
- average ring width
- density
- elasticity

1.25 × 1.25 × 20 inches (3.2 × 3.2 × 51 cm). These were dried in an oven. We then applied a load of 160 pounds (73 kg) at the midpoint of each sample to record how much it bent, or deflected, using a protocol developed by the American Society for Testing and Materials (ASTM). Density was measured by recording the masses and volumes of the samples. The ability of the samples to resonate was calculated by applying the following formula:

$$ATR = \sqrt{\frac{MOE}{\text{density}^3}}$$

## Results

Figure 1 plots the different growth rates as measured by ability to resonate (ATR) against average ring width. On average, ATR is higher for wider growth rings and more-rapid growth.



## Discussion

Contrary to expectations among many guitar manufacturers and aficionados, rapid growth and coarse grain are not associated with a lower ATR, and tight-grain, old wood does not yield a higher ATR. This suggests that tonewoods do not need to be cut from old and/or slow-growth trees to produce resonant instruments such as spruce-top guitars. This suggests that the market demand for fine-grain and/or old Sitka spruce is based more on myth or misunderstanding than science.

# Vintage Vibes for Sale!

## Vintage '75 Diva Acoustic Guitar

Seller: [Shoveltown Guitar Shop, Easton, MA](#)



(20 reviews)

Beautiful Diva from the golden age of Japanese acoustic guitar craftsmanship! Top is solid Sitka spruce with very fine grain. I've read that Sitka tops of the 1970s were cut from old-growth spruce that was about 500 years old, so you know this thing really sings! Sides and neck are mahogany, a magically warm wood. Rosewood bridge and fretboard, I'm pretty sure. Diva made amazing copies of the top American brands at the Fujigen factory in Japan until the lawsuits caught up with them. Very hard to find a Diva in this condition, because hardly anyone wants to sell! The tone is deep, warm, and resonant, and the spruce top really projects. No need to plug in this baby! You can get this tone and resonance by spending four times as much for an American-made Delphi, but this one has way more mojo! The frets have been leveled and polished but are about 70% of original height—plenty of life left! The manufacturer's label must have fallen out long ago, but the serial number stamped on the back of the headstock suggests it's from '75. Saddle and nut both appear to be bone. Tuners are original. The low E string tuner is a bit loose. Nitrocellulose finish is a bit dinged up, and there's some buckle rash on the back. The neck joint shows signs of a reset at some point. Buy now, this listing won't last long!! \$999

**\$999**



[Buy Now](#)

[Make Offer](#)

[Save to Wish List](#)

## Spot the BS

Heads up! There's some **bad science** somewhere on these pages. Can you detect which ad is making questionable claims? Which seller do you have more confidence in?

## Word to Know

In the context of stringed instruments, *intonation* is the accuracy of pitch up and down a string and across all strings of the instrument.

### Vintage '75 Delphi D-55 acoustic guitar

Seller: **Roxie's Music, Poughkeepsie, NY**



(730 reviews)

For your consideration is a gorgeous 1975 Delphi D-55 dreadnought acoustic guitar. Delphis were manufactured right here in New York, using Adirondack spruce tops and imported mahogany for neck, sides, and back. The fretboard and bridge are made of ebony. The guitar has been well cared for since 1975 by its original owner, so there are few dings and no signs of cracking in the body. Nut and saddle are cowbone. The guitar has been set up by our in-house luthier so the intonation is spot on (e.g., open A string is one octave lower than the natural harmonic at the 14th fret on the same string). The mahogany adds warmth and depth to the tone while the Adirondack spruce adds clarity and projection. Delphis from the '70s came with a certificate showing where the spruce was harvested and how old it was at the time of harvest, and this guitar is no exception: "Underhill, VT, 1973, age 380." That certificate will be included with the guitar. The original manufacturer's label is intact and in place on the inside of the guitar, with date stamp and serial number indicating a completion date of 10-16-1975 at Delphi's factory in Utica, NY. The neck joint is tight. The owner provided a receipt showing a single neck reset was performed in 1999 at the Delphi factory shop. \$2,499



**Buy Now**

**Make Offer**

**Save to Wish List**

## Consider the Source

The ads on these two pages feature used guitars described by two different sellers. What can you infer about the two different sellers based on the seller info boxes and the way their ads are written?

# Sound in Air Versus Water

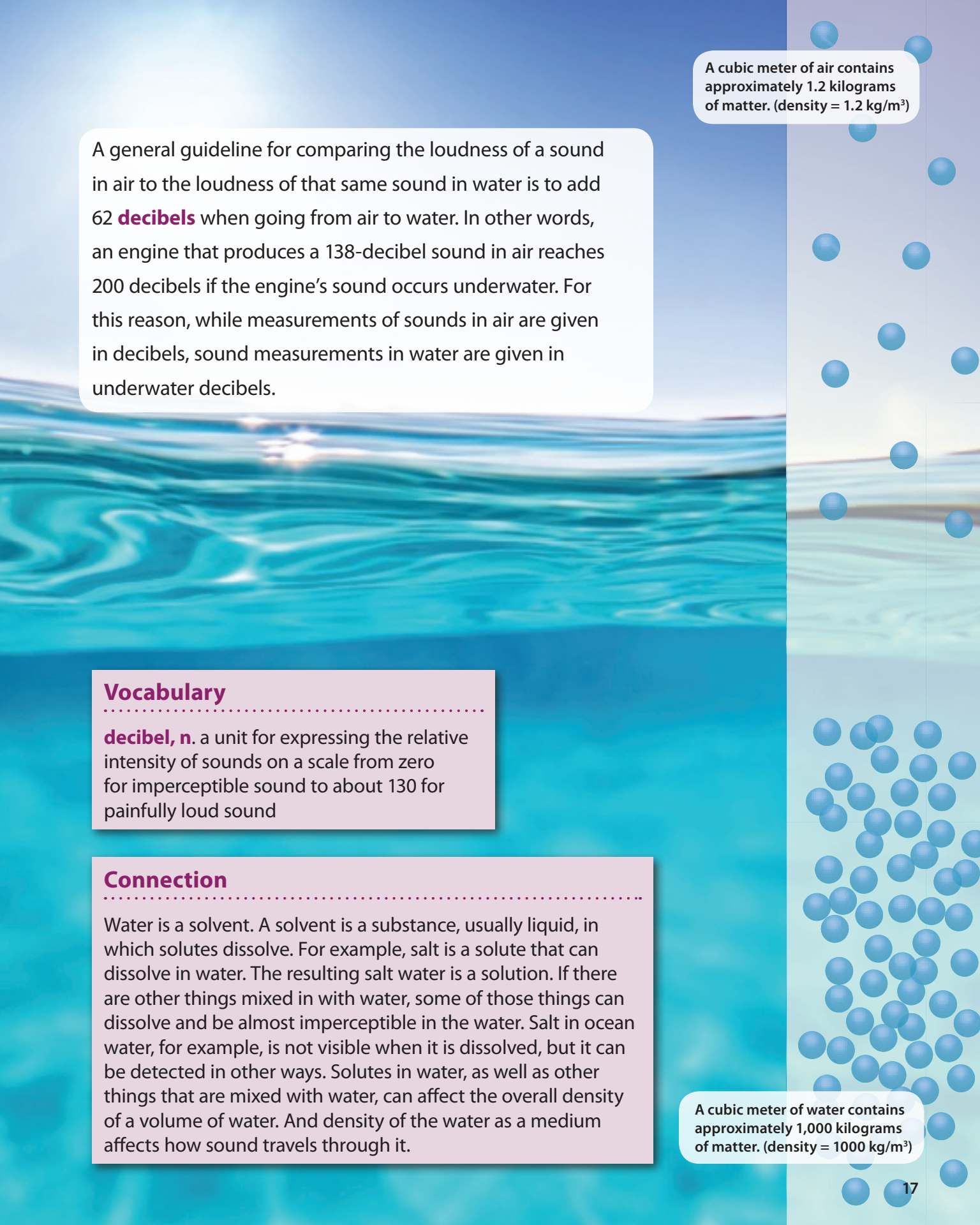
Sound waves travel more quickly under water than they do in air.

How sound travels depends on the medium through which sound waves pass. Sound travels farther (and with less loss of energy) in water than in air. If you think about the densities of air and water compared to one another, this is not surprising.

- Air is a gas, so compared with particles in liquids and solids, the particles make infrequent contact with each other.
- In liquid water, the particles are much closer together and therefore much more likely to contact with each other and transfer energy as sound waves.

At sea level, the density of liquid water is nearly 1,000 times the density of air. With so many more particles packed more tightly together, water presents a better medium than air for sound to travel through. Basically, more particles bump into one another as they move away from a vibrating source.

You can perceive this difference with your own ears when you compare how loud it sounds to tap two small rocks together in air and then underwater in a swimming pool. The underwater sound seems louder, but is it really? It is.



A cubic meter of air contains approximately 1.2 kilograms of matter. (density =  $1.2 \text{ kg/m}^3$ )

A general guideline for comparing the loudness of a sound in air to the loudness of that same sound in water is to add 62 **decibels** when going from air to water. In other words, an engine that produces a 138-decibel sound in air reaches 200 decibels if the engine's sound occurs underwater. For this reason, while measurements of sounds in air are given in decibels, sound measurements in water are given in underwater decibels.

## Vocabulary

**decibel, n.** a unit for expressing the relative intensity of sounds on a scale from zero for imperceptible sound to about 130 for painfully loud sound

## Connection

Water is a solvent. A solvent is a substance, usually liquid, in which solutes dissolve. For example, salt is a solute that can dissolve in water. The resulting salt water is a solution. If there are other things mixed in with water, some of those things can dissolve and be almost imperceptible in the water. Salt in ocean water, for example, is not visible when it is dissolved, but it can be detected in other ways. Solutes in water, as well as other things that are mixed with water, can affect the overall density of a volume of water. And density of the water as a medium affects how sound travels through it.

A cubic meter of water contains approximately 1,000 kilograms of matter. (density =  $1000 \text{ kg/m}^3$ )

# Whale Sounds

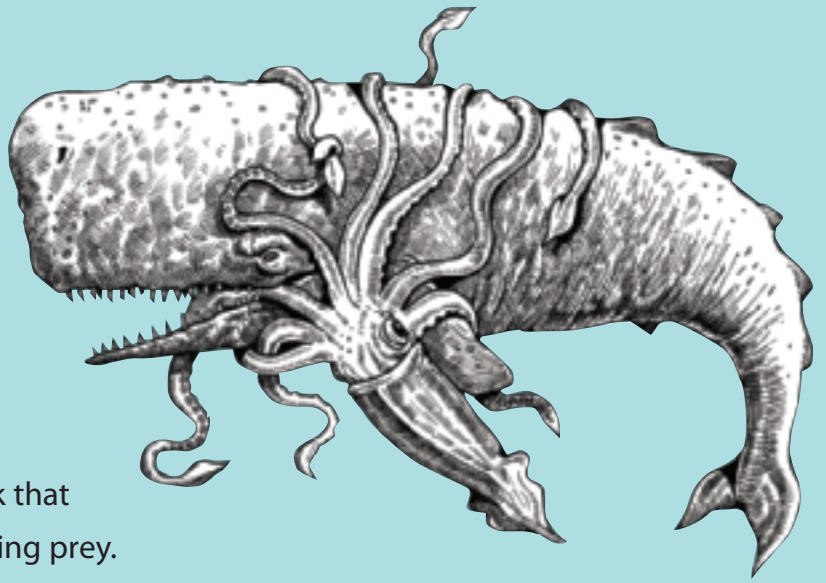
Some marine organisms have evolved ways of taking advantage of the relative ease with which sound moves through water. Many whale species use calls to communicate with each other. Humpback whales use a variety of calls, some of which are called songs, for mating rituals and other social behaviors. Some of these sounds have **frequencies** that humans can hear, and some have been considered so compelling and beautiful that recordings have been produced of humpback whale songs.

Humpback whale calls range from 40 to 4,000 hertz, or cycles per second. Blue whales, which are often cited as the largest animals to have ever lived, produce sounds with frequencies from 14 to 40 hertz. For most humans, these sounds are infrasonic, meaning we cannot hear them with our unaided ears. To perceive blue whale calls, scientists speed up recordings by about ten times, to increase the frequencies into a range that we can hear.



For several decades, whale researchers have heard a whale call at a frequency of 52 hertz in the North Pacific Ocean. The whale appeared to be on its own but calling out as though seeking companions or a pod to call home. Its call's frequency is slightly higher than that of the blue whale and fin whale, whose migration patterns are the ones that most closely match the migration of the "lonely whale." Scientists have speculated that this whale might be a hybrid of several species or a blue whale with a malformed skull. Documentary films have been produced about this whale.

Toothed whales produce calls called directional clicks. These are very brief pulses of sound that toothed whales emit in front of them so they can receive echoes from objects in the water, including prey such as deep-sea squid (a favorite of the sperm whale). This allows toothed whales to “see” in water that is so dark that their eyes are virtually useless for finding prey. This technique, called echolocation, is also found among terrestrial animals such as bats.



Sperm whale clicks range from 5 to 30,000 hertz. Orcas, sometimes known as killer whales, emit sounds that are sometimes whistle-like, along with clicks similar to those of the sperm whale. These range from about 100 to 40,000 hertz. Orcas hunt in pods, and scientists think the whales use sounds to communicate about how to approach their prey, which can include the largest whales, great white sharks, and fish hooked by commercial fishing gear, as well. A single orca can hear a fishing boat, swim toward it, and pluck hundreds of sablefish off the line before the crew can retrieve it.

Whale sounds vary in loudness, too. The blue whale's infrasonic calls have been measured at 189 underwater decibels and heard over vast distances. Scientists think blue whale calls can travel so far that whales might be communicating with each other across hundreds or even thousands of kilometers. Sperm whale clicks have been measured at 230 underwater decibels.

### Vocabulary

**frequency, n.** the number of repetitions of a process over an increment of time; for sound, the rate of oscillations, or cycles of vibration, of a sound source

### Words to Know

Description of high and low pitch of sound is subject to perception, but the measurable frequency of sounds is quantified in units called *hertz*. Hertz identify the number of cycles of a vibration of a sound source per second. Sounds that are *infrasonic* have a frequency lower than what human ears can detect; sounds that are *ultrasonic* have a frequency higher than humans can detect.

## What Is *Loud*?

It's easy to think of loudness, or the intensity of a sound, as ranging from too soft to hear—a whispered conversation a hundred feet away—to so loud that it hurts your eardrums. But what we as humans experience as soft and loud sound depends on our ears' ability to perceive different frequencies and durations.

A sperm whale click might be extremely loud in terms of underwater decibels, but if its frequency is ultrasonic—higher than what your ears can detect as information for your brain—then you would not “hear” it at all, even if you were meters away from a clicking sperm whale. Some clicks are also just tiny fractions of a second in duration—too brief for our ears to process. But your body might feel such a sound even if your ears cannot. An extremely high-frequency sound could be inaudible and yet powerful enough to rupture one's eardrums.

Likewise, a sound could be so low in frequency that your ears might not perceive it, but your body might feel it in other ways. Certain low-frequency infrasounds have been tested on people by acoustic scientists and psychologists. One experiment conducted in England exposed live audiences to several pieces of modern music. The variable that the scientists added for some of the listeners was presence of infrasonic waves,

which are too low in frequency to hear. More than twenty percent of the people exposed to the infrasounds in addition to the audible music reported strange feelings of dread, anxiety, sadness, or even a tingling of the spine.

Other studies of the effects of infrasound on humans and other animals have shown that blood pressure can be increased if subjects are exposed to high-decibel infrasound. Other symptoms or perceived sensations include eardrum damage, fatigue, and decreased alertness.

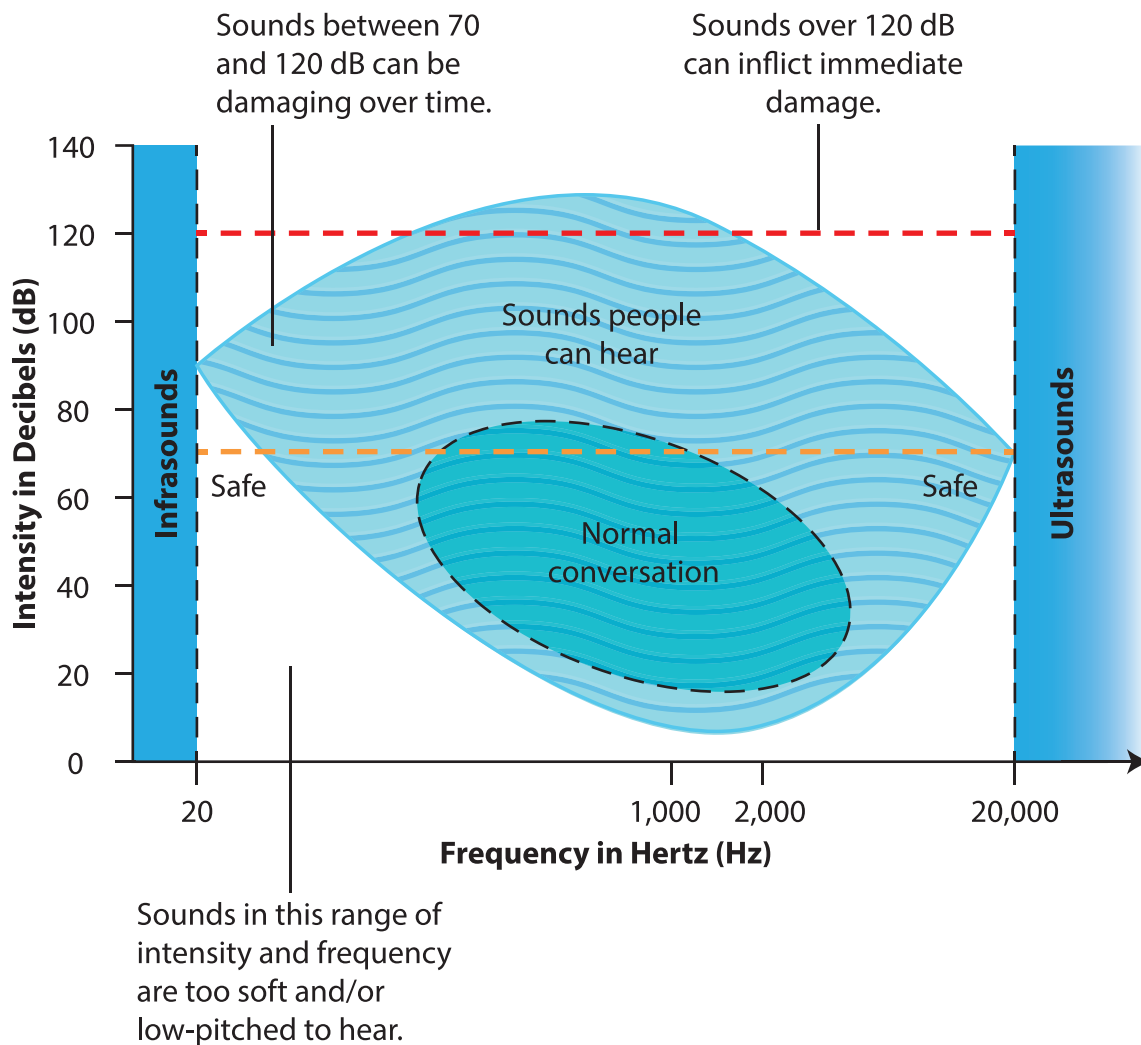
Natural sources of infrasound include earthquakes, waterfalls, wind, ocean waves, and thunder.

Human activities and machinery that produce infrasound include automobiles, aircraft, railroad engines, air compressors, and wind turbines.



The decibel scale is not linear. A sound that is 20 decibels is not twice as intense or loud as a 10-decibel sound. The decibel scale is logarithmic, meaning it is based on powers of 10. Each ten-step level on the scale represents an additional ten-fold increase

in intensity. 20 decibels is ten times more intense than 10 decibels, and 30 decibels is a hundred times more intense than 10. In terms of the natural sounds you have read about, a 200-decibel sperm whale click is about 10 billion times more intense than a human scream.



### Dig into Data

The figure shows how intensity (in decibels) and frequency (in hertz) are both variables in the human auditory field. For us to hear a sound, it has to be within a certain frequency range and within the limit and threshold in terms of intensity.

### Connection

Based on what you've read so far, do you think there is a connection between an animal's body size (structure) and the loudness of the sounds it can produce (function)?

# AMAZING Animal Sounds!

Snapping shrimp live mostly in warm seas and inhabit coral reefs. These shrimp are small but mighty! They can produce very loud sounds with their claws. For example, a snapping shrimp uses its specialized claw to produce a sound so loud that it stuns nearby prey. When the shrimp is going to stun its prey, one set of muscles opens the claws while another is producing tension

as if to close it. The first set relaxes, causing the tension of the other muscles to slam the claw shut so fast that an empty bubble occurs in the water. Almost as soon as this vacuum is formed, the pressure of the sea crushes it with so much force and speed that a very loud sound results. The vibrations are so powerful that they can stun or kill small animals in the immediate vicinity.

There are so many snapping shrimp doing this across so many different marine habitats that a symphony of snaps is playing in seas all over the world. In addition to producing a 200-decibel snap, the implosion of the bubble can emit light as well as a flash of heat!

While sound travels well in water, many organisms that live in water do not have the physical means of making sound. Whales and other marine mammals are air breathers, and they can use inhaled air in some way to generate sound. Snapping shrimp have specialized claws. Some fishes have ways of croaking, grunting, moaning, or emitting other sounds, but they are not particularly loud. To find other animals that make sound, we must leave the water.





One of the loudest terrestrial animals is the elephant. The range of sounds elephants can produce is wide in both intensity and frequency. They emit and hear infrasonic (to our ears) sounds as low as 5 hertz and high-pitched sounds of 16,000 hertz. Elephants' ears take in sound waves, but elephants can also perceive low-frequency rumblings through their large feet and their trunks when pressed against the ground. Scientists think elephants can communicate in this way over distances without alerting other animals to their presence.



Among insects, cicadas are extremely loud. Australia's green grocer cicada, *Cyclochila australasiae*, can achieve sounds as loud as 120 decibels at 4,300 hertz.

The greater bulldog bat, *Noctilio leporinus*, of Panama can emit high-frequency sounds of 140 decibels. These are for echolocating prey in the night sky.



Terrestrial animals' calls do not travel as far or as reliably as aquatic animals' calls. In air, sound energy tends to get absorbed and lost as particles in the air bump into each other in a less orderly way than in liquids or solids. Wind can also disrupt the movement of sound through air. The high-pitched chirps of the greater bulldog bat are most likely effective only at relatively close range—such as finding a flying insect that is inches away.

### Connection

In the last article, we asked, "Based on what you've read so far, do you think there is a connection between an animal's body size (structure) and the loudness of the sounds it can produce (function)?" After reading these two pages, would you modify your answer?

# Noise Pollution

A dramatic rescue effort is underway as volunteers try to comfort stranded pilot whales in a shallow bay in New Zealand. The exact causes of mass strandings are unclear, but some scientists think that disrupted communication could play a part.

Scientists are concerned about noise pollution in the ocean. In a sea that is noisy with human activity, whale calls can be drowned out or disrupted. A pod of whales whose communication is disrupted can end up going in the wrong direction. Whales that are attempting to find mates might expend much more energy than they normally would, or fail to find mates all together.

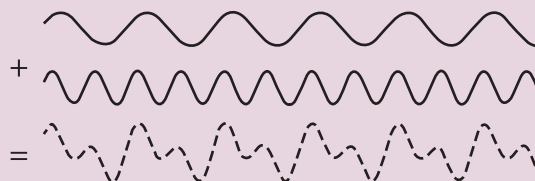
Garbled communication is only one of the threats human-produced sound introduces to whales. Seismic survey vessels, in search of deposits of petroleum and natural gas, use powerful air cannons to send sound



waves toward the ocean floor. Whales can be injured if they are nearby when these cannons are fired. To avoid harming whales, survey vessels must avoid using their air cannons in certain areas where whales are likely to be found. Or they must employ observers who scan the waters for any sign of whales and signal the captain to halt operations until the whales have moved out of range of the air cannons.

## Connection

Like two water waves that collide and cancel each other out, sound waves can collide or overlap, producing a garbled sound. It's called sound interference. Here's a model of one way interference among sound waves can happen.



## Tipping the Balance of Nature . . . with Noise

*Is a noisy compressor on a natural gas well a bad thing or a good thing?*

That depends on whether you are a piñon tree or a wildflower, a hummingbird or a scrub jay.

Scientists are beginning to realize that noise pollution can have indirect effects on plant life as well as animals. When birds are spooked by noise, they leave an area. Plants that depend on those birds to scatter their seeds can decline.



For example, piñon pines of the American Southwest depend on scrub jays to scatter and bury their seeds. People have built natural gas wells, powered by noisy compressors, on a great deal of piñon pine forest land in New Mexico. When there is too much noise near a piñon pine, the jays do not show up to pick seeds from that tree's pinecones and bury them in the soil. Without the jays to provide this service, that particular tree is less likely to reproduce.

If many trees in the area suffer the same fate due to noise pollution, then whole stands of piñon pines could decline over time. But what's left is not necessarily a barren wasteland. Where fewer trees shade the ground, low-blooming plants fill in. Hummingbirds and other pollinators seem less bothered by the noise. Hummingbirds even benefit from the absence of the jays, which sometimes eat the hummingbirds' eggs and young.



### Consider the Sources

Articles about this topic can be found online. Two published by *The New York Times* and National Public Radio both cite Clinton Francis, an evolutionary ecologist at the National Evolutionary Synthesis Center in Durham, North Carolina, and his research published in *Proceedings of the Royal Society B: Biological Sciences*.

# The Matter Matters

Sound has to travel through a **medium**—a solid, a liquid, or a gas. Does the medium make a difference to the sound? It does. The matter sound travels through affects the speed and efficiency with which sound transfers.

## Vocabulary

**medium, n.** an intervening substance through which a force acts or an effect is produced

## Sound in Solids

In general, solids that are very dense are also very rigid, so an increase in density is usually associated with an increase in rigidity. This means that most solids that are stiff and dense will allow a high speed of a sound wave. Iron, for example, allows for a much higher speed of a sound wave than lead, which is softer than iron.

## Connection

**Look for a pattern.** Which of the solids in the table do you think is the most elastic? What does elasticity mean for sound transmission?

Speeds of Sound Waves in Solids	
Solid	Speed of Sound Waves (meters per second)
Aluminum	6,320
Beryllium	12,890
Copper	4,600
Glass	4,540
Gold	3,240
Iron	5,120
Lead	1,210
Mahogany (wood)	4,970
Rubber	60
Sitka spruce (wood)	5,000

## Words to Know

The speed of a sound wave (often called the *speed of sound*) is known as *acoustic velocity*. The symbol  $v$  represents this. It can be calculated in any medium by knowing two properties of the medium: its density ( $\rho$ ) and its bulk modulus ( $B$ ). The bulk modulus is a measure of how easy or hard it is to compress or bend the medium.

The equation is:

$$v = \sqrt{\frac{B}{\rho}}$$

**Reader Tip:** This isn't something you need to try to memorize. Something related to it will come up later in the reading to refresh your memory.

## Sound in Liquids

Speeds of Sound Waves in Liquids	
Liquid (room temperature)	Speed of Sound Waves (meters per second)
Ethyl alcohol	1,207
Glycerine	1,920
Kerosene	1,324
Mercury	1,450
Oil (lubricating)	1,461
Water (distilled)	1,493
Water (ocean)	1,522

### Connection

Ocean water has a higher speed of sound than pure water because the dissolved salt increases the water's density. In the ocean, speed of sound increases with depth—that is, as the pressure and salinity increase. Warm water is usually near the surface, whereas saltier, colder water sinks to the ocean floor. A one-kilometer increase in depth means an increase of 17 meters per second to the speed of sound.

## Sound in Air

All air isn't equal. Temperature and atmospheric pressure vary. And those variations affect the way sound waves move through the air.

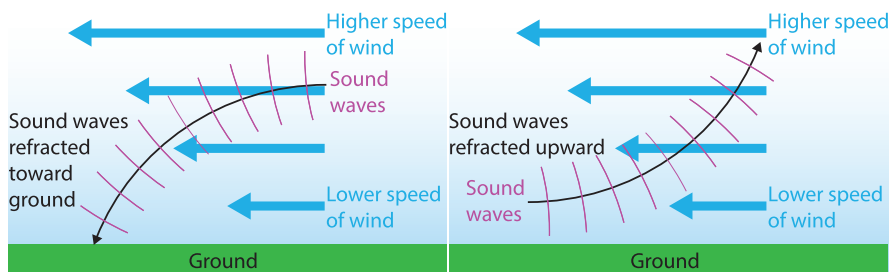
### Dig into Data

What relationship is evident between atmospheric pressure and temperature?

Sound Waves and Altitude				
Altitude (feet)	Barometric Pressure (inches of Hg)	Temperature (°C)	Temperature (°F)	Speed of Sound Waves (meters per second)
0	29.92	15.00	59.00	340
5,000	24.89	5.09	41.20	334
10,000	20.58	-4.81	23.30	328
15,000	16.88	-14.72	5.50	322
20,000	13.75	-24.62	-12.30	316
25,000	11.10	-34.53	-30.20	309
30,000	8.89	-44.44	-48.00	303
35,000	7.04	-54.34	-65.80	296
40,000	5.54	-56.50	-69.70	295

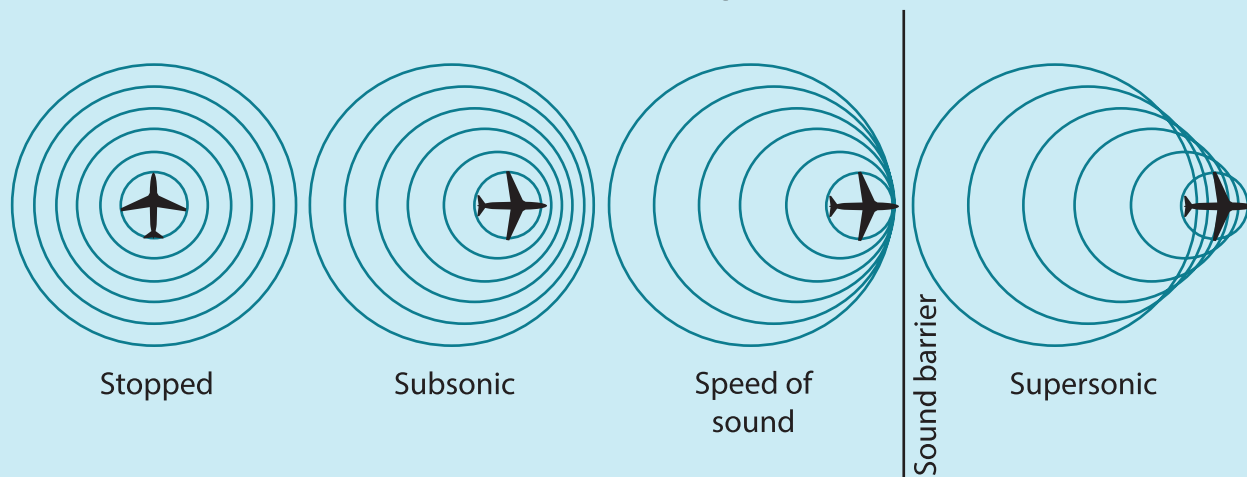
### Wind's Effect on Sound

Sound waves bend, or refract, down toward the ground if they are traveling with the wind. If they are traveling against the wind, they refract up into the atmosphere.



# Breaking the Sound Barrier

## Pressure Waves of Air Flowing Off an Airplane



Sometimes the numbers associated with scientific measurements get really big. The Mach scale is used to describe high speeds at which some objects can move on Earth. When an object reaches the speed of a sound wave (which is commonly called *the speed of sound*), it is at Mach 1. If an object is traveling at Mach 2, it is moving at twice the speed of sound. Each full Mach represents a multiple of the speed of sound.

It's important to note that the speed of sound waves depends on the medium in which the object is traveling (and the specific properties of the medium in that location). Air is the only medium through which we are likely to observe objects traveling at or near the speed of sound, so when we talk about an object going Mach 1 or Mach 2, we are talking about objects in Earth's atmosphere.

The speed of sound waves in air is slower at higher altitudes, where temperature and

pressure are low. This makes it easier for an object, such as a meteorite or airplane, to break the sound barrier at high altitude than it would be near Earth's surface.

The sound barrier is not a physical wall, but for the object approaching the speed of sound, it can feel like there is a kind of barrier just ahead of it. This is because the sound waves moving in the same direction as the object are accumulating, like the bow wave in front of a moving ship. The object is moving slightly slower than the sound wave, causing sound waves to pile up in front of the object. When the object goes slightly faster and gets past the sound waves, suddenly all that built-up pressure is forced behind the object. A powerful shockwave produces a loud crack sound, called a sonic boom. Lightning, gunshots, and even the crack of a whip all produce sonic booms because the sound barrier has been broken.

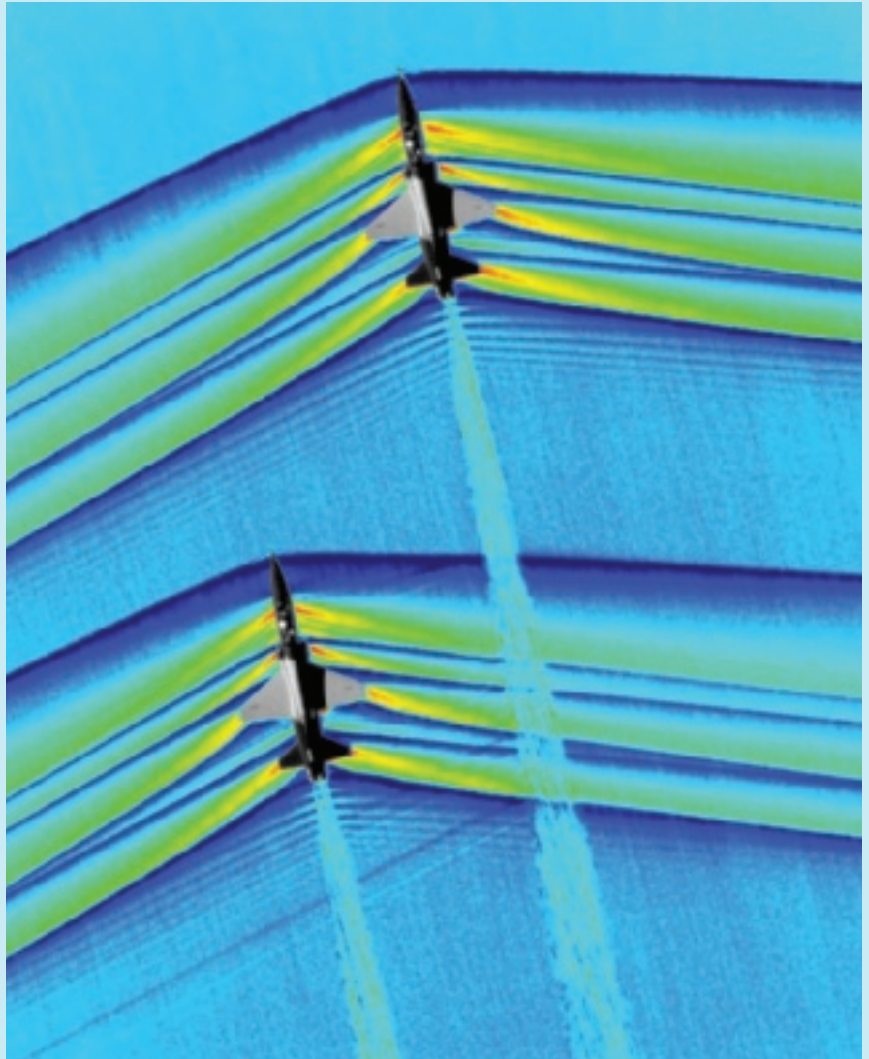
## Supersonic and Hypersonic

Special airplanes have been breaking the sound barrier since 1947. Many fighter planes can travel several times the speed of sound, but they are not necessarily designed to do so on every flight. True supersonic aircraft are those that are designed to fly at Mach 1 or greater.

The SR-71 Blackbird is a supersonic airplane capable of traveling at Mach 3. It was a spy plane for the United States. By flying at very high altitudes and supersonic speeds, the Blackbird could take photographs of Earth secretly—as high as 85,000 feet above the ground! The Blackbird was designed to fly at the speed of sound or greater, so it is not meant for maneuvering in tight spaces or designed for combat like some other military planes.

The Concorde was a supersonic airliner—a plane that carried passengers—that took people between North America and Europe in just a few hours. After twenty-seven years of service as an airliner, it was retired in 2003 because of the high cost of operating a supersonic aircraft.

While the Concorde has been shelved, research into supersonic airliners continues. There are also some experimental aircraft that can travel between Mach 5 and Mach 10, a range called hypersonic. In theory, a hypersonic airliner could cross the Pacific Ocean in a few hours.



When aircraft fly faster than the speed of their sound waves, the effect of the pressure waves they produce is briefly visible. This NASA image captures the phenomenon as the two planes are about to break through the sound barrier. The image is colorized to make the effects more visible for research.

### Consider the Source

NASA is the National Aeronautics and Space Administration, the United States' premier research agency for exploring space and developing technologies for high-altitude flight.

# The Acoustic Soundscape



*I wonder about the trees.  
Why do we wish to bear  
Forever the noise of these  
More than another noise  
So close to our dwelling place?  
We suffer them by the day  
Till we lose all measure of pace,  
And fixity in our joys,  
And acquire a listening air.  
They are that that talks of going  
But never gets away;  
And that talks no less for knowing,  
As it grows wiser and older,  
That now it means to stay.*

Robert Frost (1874–1963)

The lines beside the open window are an excerpt of Robert Frost’s poem “The Sound of Trees.”

Frost describes his perception of the sounds trees make. The trees are in perpetual motion, making the poet think the trees sound as if they are about to go someplace, though they never leave. And he wonders what it is about the sound of trees that makes us want to live where we can enjoy hearing them.

The trees that Frost heard might have been leafy and green. The density of foliage on the trees would have characterized the sounds that inspired the poet. Or their leaves might have been autumn brown and crackling. The humidity and temperature of the air might have been another factor affecting the transmission of sound. Had Frost sat in the forest in winter, the absence of foliage and the presence of cooler, drier air might have made the poet write a very different poem because the sounds would have been different to his ears.

Poets, painters, and other artists, and therefore their crafts, have been inspired by light and sound waves for as long as humans have made art.

The sound waves we receive might have passed through, refracted or reflected off, or been partially absorbed by a variety of different media in our environment. Even in one location—say, your own yard—you might experience sound very differently depending on the weather or other factors in the acoustic soundscape. Foliage and other materials in an environment vibrate in different ways. Consider a tall pine tree. All those branches, bearing all those needles, can produce sound waves by vibrating differently in different moments. They can absorb other sounds, too. A large stand of pine trees in an urban park can stop noise from one side of the city from reaching the other. This is among the reasons why urban planners place high value on trees. They can provide sound absorption (as well as cooling shade) over a lifespan of tens or hundreds of years.

## Words to Know

*Acoustic* means related to sound. The *acoustic soundscape* refers to the combined properties and behaviors of sounds in a given physical environment.

Snowfall is another natural phenomenon that can quiet the acoustic soundscape. Billions of hexagonal ice crystals contain small pockets of air, allowing snowfall to act as a sound-absorbing blanket. A surface that would have reflected sound waves instead acts as a dampener. Falling snowflakes also block the movement of sound waves through the air.

Sound absorption is based on a scale from 0 to 1, and a snow-covered landscape can rate between 0.6 and 0.8. The overall effect is a silencing of background noise, particularly sounds from afar. This explains why many people find a snow-filled landscape so peaceful and calming. If the snow begins to melt and then freezes to hard ice, the sound-absorbing landscape transforms to a highly reflective soundscape.

### Connection

**Structure and Function:** What differs between interior rooms that are loud or have echoing, hollow sounds and rooms that have softer, muffled sounds?



This cardinal's song might be somewhat muted by the sound-absorbing snow around it, but with a lot of background noise filtered out, the song might be easier to perceive.



If it isn't coated with snow, a frozen lake's solid surface will reflect sounds that strike the top of the ice and transmit sounds within the ice, like the skin of a drum.

# Using Sound to Measure the World

*“One, one-thousand,  
two, one-thousand,  
three, one-thousand . . .”*

## Low Tech: Lightning to Thunder

Have you ever done a rough calculation of a thunderstorm’s distance by counting the number of seconds between a flash of lightning and the sound of thunder?

One calculation goes like this: Count the seconds between the flash and the sound; then divide by five to get the distance in miles. This is based on the basic formula for calculating distance using a rate and a time: distance = rate  $\times$  time.

The speed of sound waves in air is, on average, about 12 miles per minute. That’s one mile per five seconds. So, to arrive at a figure for distance in miles, take the elapsed time between the flash of lightning and the sound of thunder, in seconds, and divide by five.

The accuracy of this “flash-to-bang” calculation can be thrown off by factors such as the

humidity, elevation, and temperature of the air through which the clap of thunder travels. Humidity means more particles in the air, which makes it easier for sound to travel more quickly. Warmer air is denser, which also means more particles closer together. The calculation could, in theory, be tweaked to account for these variables, but since the calculation is used only in relatively small areas—where a person observes the flash of lightning—any calibration of the calculation would have only a minor effect.

### Dig into Data

If you count five seconds between lightning and thunder, and then three, and then one, what does this tell you about the thunderstorm’s path?

## High Tech: Sonar

There is a great deal more to Earth than the surface on which we live. How do we explore or make sense of the majority of Earth, which is made of depths of solids and liquids into which we cannot physically go?

A fraction of Earth's liquid water can be explored visually, by putting on scuba gear, getting into submarines, or using remote-operated vehicles fitted with cameras. The rest is too murky, dark, cold, and dangerous. We can dig into Earth's crust, but we've only scratched the surface. To explore the rest of the hydrosphere and geosphere, scientists have used what they've learned about sound to find new ways of "seeing" the unreachable depths of Earth's land and water.

Sonar, which stands for "**s**ound **n**avigation and **r**anging," is a human technology inspired by the echolocation used by marine mammals such as dolphins and sperm whales. In sonar technology, sound waves are emitted in the direction of a target, such as the ocean floor or an area where

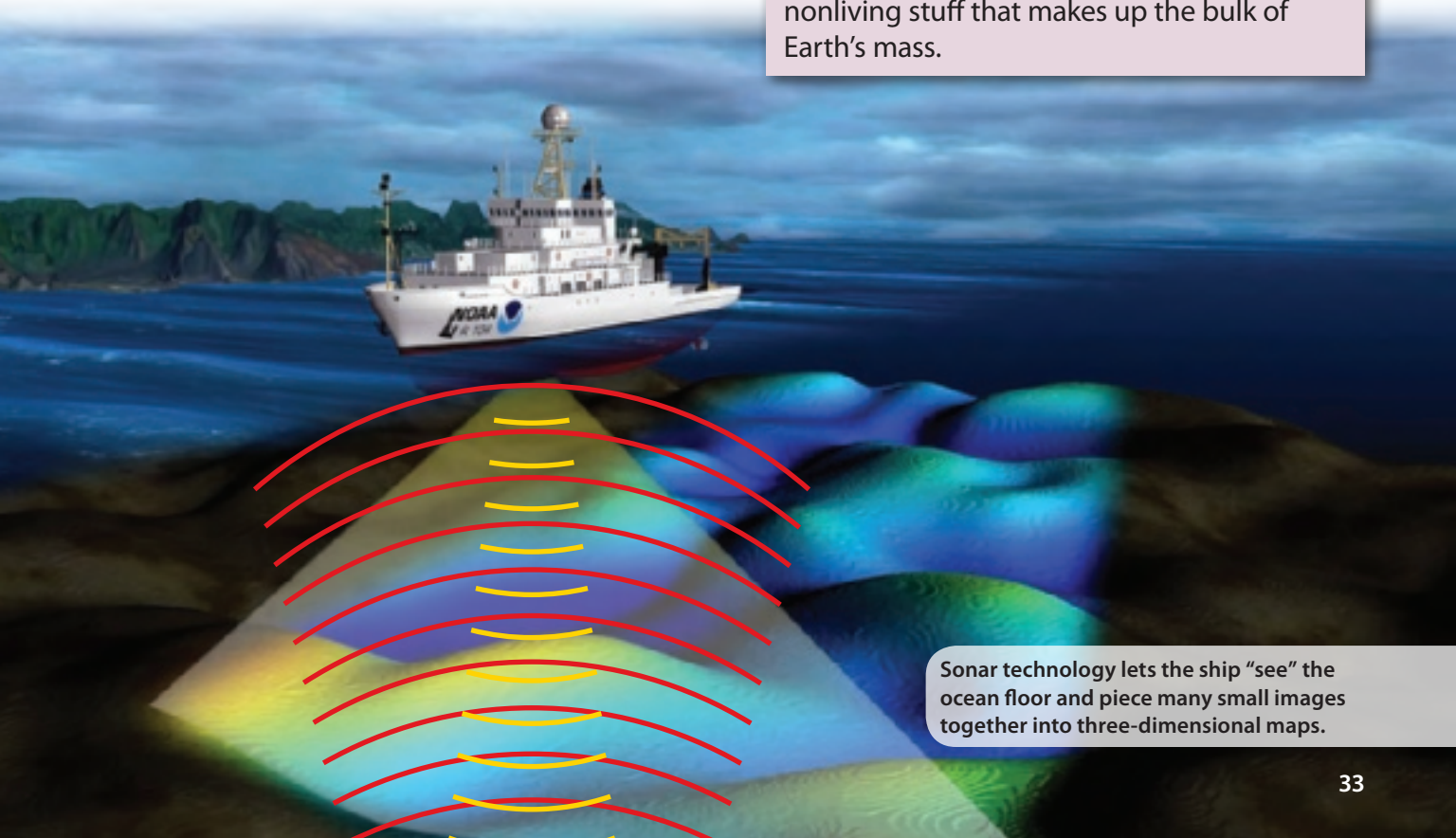
fish might be. If sound waves reflect off objects and arrive back at the starting point, they are detected, and then the overall time it took for the waves to get there and back can be used to calculate how far away the objects are.

This is similar to calculating the distance of a lightning strike by listening for thunder and counting the seconds in between the flash and the bang. But in sonar's case, the time is doubled because it is the echoed sound that is being detected.

Sonar has been used to locate fish, whales, submarines, shipwrecks, and the precise contours of the ocean floor. Coupling sonar technology with GPS has allowed humans to produce detailed maps of the 70 percent of Earth's solid surface that happens to be underwater.

### Connection

Recall that the hydrosphere is all of the water on Earth. The geosphere is all of the solid, nonliving stuff that makes up the bulk of Earth's mass.



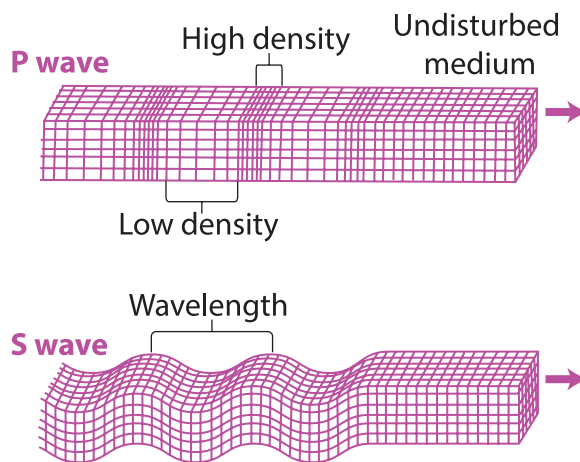
Sonar technology lets the ship "see" the ocean floor and piece many small images together into three-dimensional maps.

# Seismic Waves

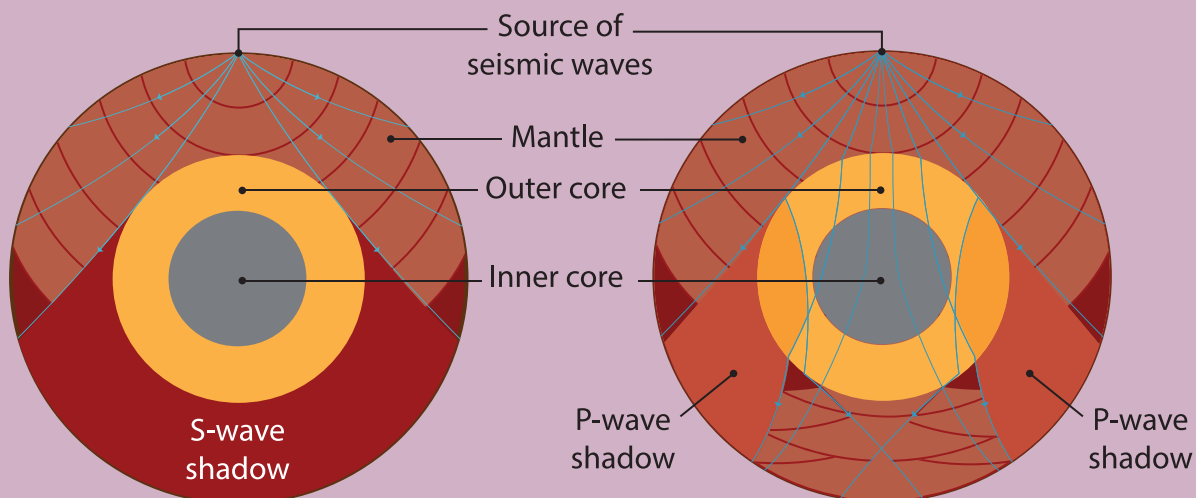
An earthquake produces vibrations in Earth's crust that are similar to the vibrations that occur in sound waves. Particles in the medium vibrate, transferring energy between them. Both earthquakes and sounds transmit energy through compression waves.

Earthquakes produce primary waves, called P waves, and secondary waves, or S waves. P waves move faster and can travel through liquids and solids. S waves are slower and cannot pass through liquids. Like sound waves, P waves are compression waves. S waves roll up and down like ocean waves.

The speeds and paths taken by seismic waves, waves through Earth's crust, can be analyzed to produce pictures of the interior of Earth. Where the seismic waves change speed or direction or cease, it means they've encountered a difference in the material they are passing through.



After an earthquake, S waves are not detected over a relatively wide swath of Earth's surface on the opposite side of the globe. This suggests that the outer core of Earth is liquid. How do we know the entire core is not liquid? The manner in which P waves bend, or refract, through Earth's center suggests that the inner core is solid. The S-wave "shadow" is proof of the liquid outer core while the P-wave shadow proves that the inner core is more solid.



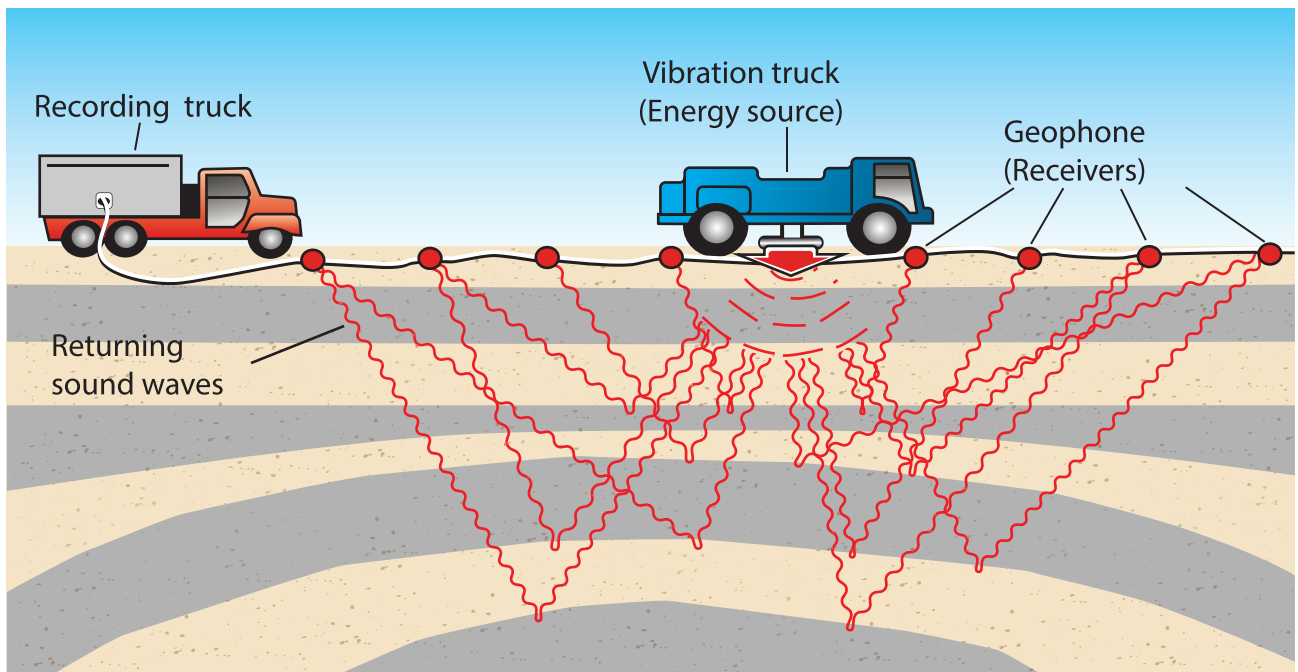
## Surveying with Seismic Waves

As with sound waves for thunder, the travel times of seismic waves can be used to calculate distance, too. The ways seismic waves reflect and refract can be interpreted to pinpoint where Earth's crust changes in materials. This can be done by producing a strong vibration at the surface of Earth's crust.

Oil and gas companies conduct seismic surveys to find deposits of petroleum or natural gas deep below the surface. If natural gas or petroleum deposits are in the area, then it is likely that someone will drill down into the ground to draw the material to the surface. As with sonar, using seismic waves to "see" into the ground requires wave producers and wave receivers.

To survey a relatively shallow area, a sledgehammer striking a steel plate will suffice. To send waves deeper, a large weight can be dropped, dynamite charges can be buried and exploded, or a special vibration truck can send vibrations down into the ground.

The diagram below illustrates how a vibration truck pounds the ground like a drum. Waves move through the ground, and some are reflected back toward a series of geophones, which send signals to a recording truck that sorts out the data. The different times it takes for waves to bounce back to the surface are compared, as are the strengths of the reflected waves. These data can be used to produce a picture of what's deep below the surface.



### Word to Know

*Seismic* refers to earthquakes or other vibrations of Earth's crust.

# The Loudest Sound on Record

On August 27, 1883, at 10:02 a.m. local time in the Sunda Strait of the Indian Ocean, the Indonesian island of Krakatau (also called Krakatoa) exploded during a volcanic eruption. What was a 2,700-foot volcanic peak became a smoldering shell of its former self just minutes later. Six cubic miles of rock were blasted into dust and debris that flew across the region and filled the sky. A tsunami over 100 feet in height swept across nearby islands, killing at least 36,000 people in a matter of minutes. It was a devastating event locally, but it also produced what was possibly the loudest sound ever recorded.

Over two thousand miles south of the eruption, farmers in Alice Springs, Australia, heard what sounded like two gunshots. On Diego Garcia, an island in the Indian Ocean two thousand miles west of Krakatau, the cracking sounds were also very clear and cannon-like.

Closer to the eruption, the sound was more deafening—literally. Sailors on the British ship *Norham Castle* some forty miles from Krakatau suffered catastrophic injuries to their ears.



The captain wrote in his log:

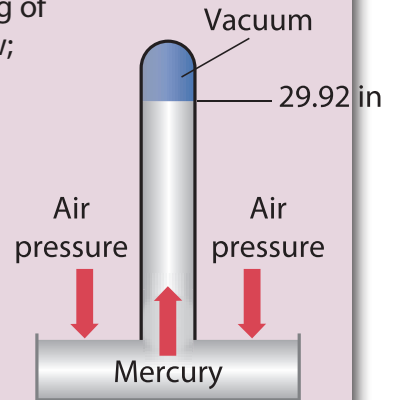
*A fearful explosion. A frightful sound. I am writing this blind in pitch darkness. So violent are the explosions that the eardrums of over half my crew have been shattered. My last thoughts are with my dear wife. I am convinced that the Day of Judgment has come.*

About 100 miles away, in Batavia, a barometer recorded a 2.5-inch change in atmospheric pressure, suggesting a sound as loud as 172 decibels had swept through. For anyone who experienced such a powerful wave of sound, it would be like standing next to a rocket as it blasted off into orbit. That this sound was experienced a hundred miles from the source is astounding. Coastal inhabitants who were not killed by the tsunami that swept across low-lying areas of the region most likely suffered permanent damage to their ears.

The disturbance in the atmosphere caused by the explosion of Krakatau traveled across the globe and was audible up to 3,000 miles or so away. Barometers all around the world registered waves of compressed air. In fact, the pressure waves kept going for about three days, showing similar spikes in pressure at weather stations around the world every thirty-four hours. All of these data suggested that waves from the explosion were traveling at approximately the speed of sound.

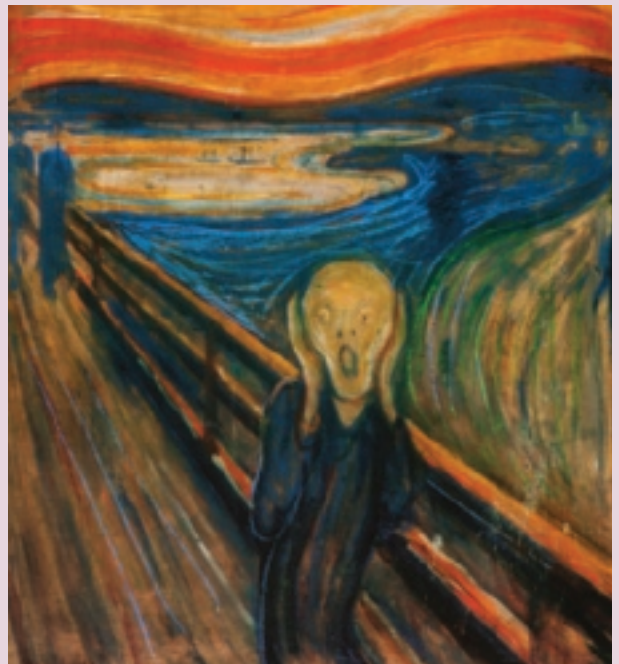
### Connection

A barometer reading of 26 inches is very low; a reading of 32 inches is very high. That is only a difference of 6 inches between the two extremes. So a sudden change of 2.5 inches is quite dramatic!



### Connection

The dust Krakatau emitted into Earth's atmosphere produced intense sunsets that inspired famous artworks for more than a decade, including Edvard Munch's "The Scream." How do you suppose art historians made the connection between the eruption of Krakatau and artworks of the period?



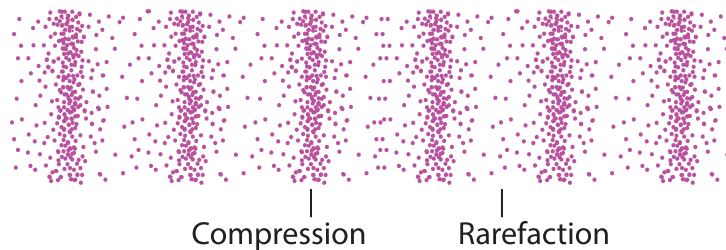
# Compression Wave Action

Picture yourself as a passenger near the back of a very crowded subway car. You and your fellow passengers are all standing up, with no more than an inch between you. Someone at the front of the car sneezes violently, causing him to bump into the person next to him. She then bumps against the person behind her, who bumps into the next person, and so on, until you are bumped, causing your elbow to gently knock into the window at the end of the car. The moment passes, and nobody has actually changed positions inside the subway car, because neither the sneezer nor anyone after him shifted their feet. Nonetheless, energy in the form of motion was transmitted to and from all of you, and in the end, some of that energy was transferred into the sound of your elbow knocking into a plexiglass window. The energy moved in the same direction as the initial disturbance. This is a model of a **longitudinal wave**.

This model illustrates how sound waves travel. A disturbance presses against a band of particles in the air. Those particles bump into others nearby. Each band of bumped particles is compressed; the particles in that collected area are pressed more closely together. And the band is called a compression. The compression travels in the same direction as the disturbance. As the compressions move, less-pressurized areas are formed between them. These low-pressure areas are called rarefactions. Keep in mind that particles themselves are not travelling in the direction of the energy. A particle that finds itself in a compression in one split second is likely in a rarefaction a split second later. The individual particles are vibrating, and they end up back where they were before the disturbance. The rate of change between compression and rarefaction is similar to the frequency of the wave.



Longitudinal wave



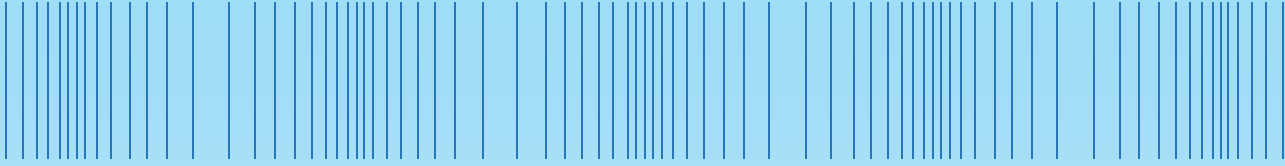
Particles do not change position as a result of sound. They are bumped, but only for a moment. They might be moved to new positions by other forces, such as wind or simply bouncing off each other, but sound does not transport them from one point to another, or push them along. It just disturbs them in place.

## Vocabulary

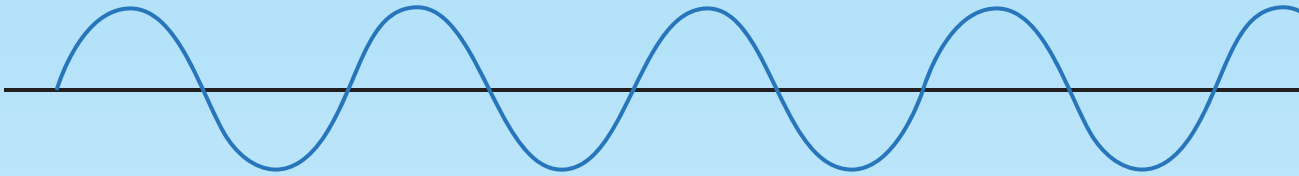
**longitudinal wave, n.** a wave that vibrates in the direction in which it propagates

## Contrasting Wave Models

A sound wave is a longitudinal wave. Particles vibrate parallel to the direction of the wave's movement. Longitudinal waves are mechanical waves. They require particles in a medium to transport their energy. Here is another way of representing the compressions and rarefactions in a longitudinal wave.

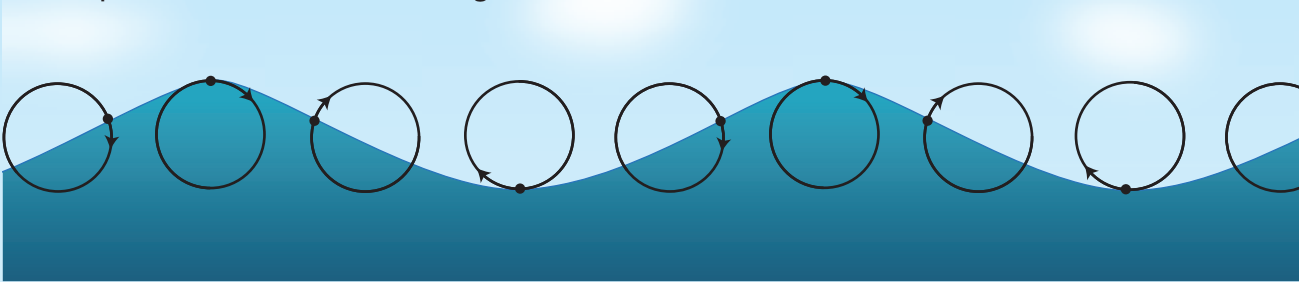


A light wave is a transverse wave. Electromagnetic waves are nonmechanical. They can transmit energy through a vacuum. They do not vibrate matter, but they do have amplitude and frequency that can be modeled in a line diagram like this one.



Surface waves in water resemble both longitudinal and transverse waves. They present a distinct crest-and-trough shape, but particles in the medium oscillate in circles rather than moving back and forth or up and down relative to the wave propagation.

A molecule of water in an ocean wave moves in a circle without traveling in the direction of the wave's forward motion. Similarly, an object floating on the surface bobs up and down without traveling forward with the wave.



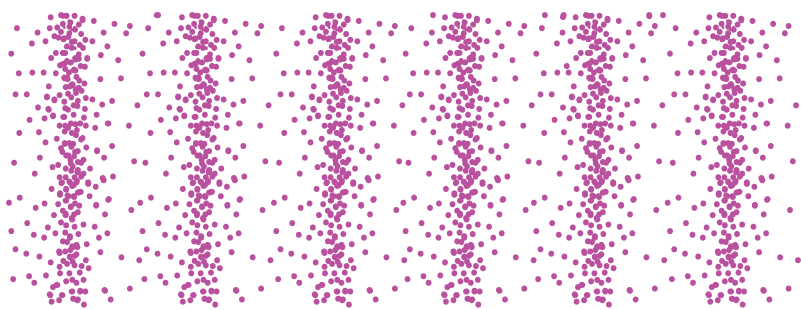
### Connection

Sound and light both travel in waves, though of different types. The most visible and familiar waves are those that move through water. What's the difference?

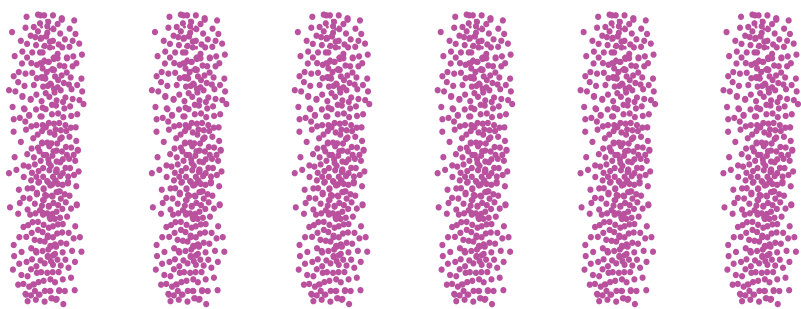
# Sound Waves Versus Shockwaves

The globe-circling sound of Krakatau's explosion in 1883 is considered the loudest in recorded history based on first-person accounts and physical measurements that were recorded both in Indonesia and around the world. Because of the molecular nature of the gases that make up air, the loudest possible sound in air has a value on the decibel scale of 194 dB. At this point, the wave's compressions and rarefactions are so extreme that they are an all-or-nothing phenomenon of pressure: about twice the normal atmospheric pressure inside the compressions but no pressure at all—a vacuum—in the rarefactions.

Because rarefactions cannot get any emptier than a vacuum, this is the limit of what can be considered a "sound." Beyond this point, any additional energy in the wave causes the compressions to actually push particles of air along, like a snowplow through a drift of snow. The particles are no longer merely vibrating; they are being moved to new locations. This is a shockwave. (Take another look at the photo back on page 29!)



Particles in a longitudinal sound wave



Particles in a shockwave

## Word to Know

A *shockwave* is a high-pressure mechanical wave that pushes particles out of their original positions.

## Connection

In water, because the particles are closer together and the pressure is higher to begin with, sounds greater than 194 decibels are possible, as you read about in a previous selection mentioning sperm whales and snapping shrimp.

## The Chelyabinsk Meteor

On February 15, 2013, a meteor collided with Earth's atmosphere over Chelyabinsk, Russia. As it entered Earth's atmosphere, the meteor was the size of a small building and weighed about 10,000 metric tons. It was also moving at about 40,000 miles per hour—sixty times the speed of sound. Its mass and speed led to friction with the atmosphere so intense that the fiery light it emitted was brighter than the sun. The meteor exploded with the energy of 460 kilotons of TNT, or about thirty times what was unleashed by the atomic bomb that exploded over Hiroshima, Japan, during World War II.

The actual sound of the meteor breaking up was infrasonic, or below what human ears could perceive, but intense enough to circle Earth twice. However, fragments of the meteor that continued to fall toward Earth, burning up along the way, produced sonic booms that were audible and recorded in videos taken from the ground as people witnessed the fireball coursing through the sky. The explosion also produced shockwaves that shattered millions of square



feet of glass in windows and even knocked down a brick wall of a nearby factory.

Shockwaves from other natural disasters have devastated Earth's surface. An even larger meteor exploded in the atmosphere in Russia on June 30, 1908. The Tunguska event flattened 800 square miles of forest, even with very little debris reaching the ground in the form of meteor fragments, known as meteorites. Scientists estimate that the Tunguska meteor's explosion was six times as powerful as the Chelyabinsk event.

Sixty-five million years ago, Earth's history was put on a new trajectory when an asteroid struck Earth in what is now the Yucatán region of Mexico. Although a controversial theory, the shockwave and other products of the impact of that asteroid may have wiped out 80 percent of life on Earth, including the dinosaurs.

## Sound in 3-D

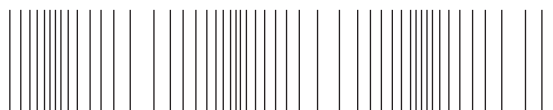
You've read that sound travels in longitudinal waves. Most visual models of longitudinal waves are like the diagrams you've seen in these articles. Energy is moving in one direction, usually from one side of a page to the other. In a figure showing sound waves, the compressions and rarefactions are parallel bands that suggest motion across the page.

The image to the right models what happens to particles in a single two-dimensional plane. The particle vibrations are only represented relative to the page and your vantage point. But how does sound move in the actual, three-dimensional world?

Think of the waves that radiate from a raindrop on a pond surface. The surface

wave might be diagrammed as a single line. But in the photograph you can see that the waves are moving outward from each point of disturbance in all directions, 360 degrees.

2-D



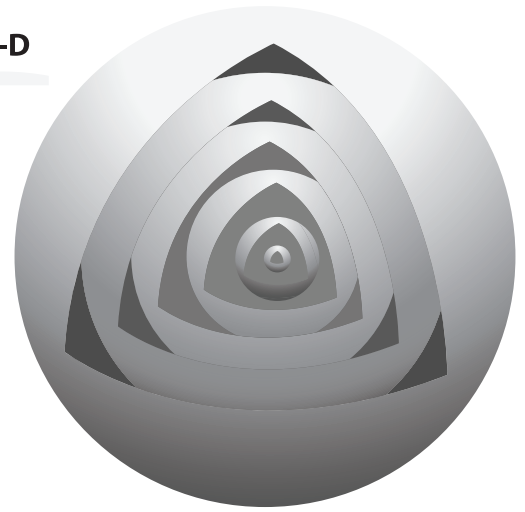
### Word to Know

A *plane* is a flat region (think "surface") in which, if any two points are chosen, a straight line joining them lies entirely on that surface.



With sound, the outward movement isn't limited to a 360-degree circular region on a flat surface. The sound emanates out from the source in all directions, so imagine sound waves travelling as a growing sphere.

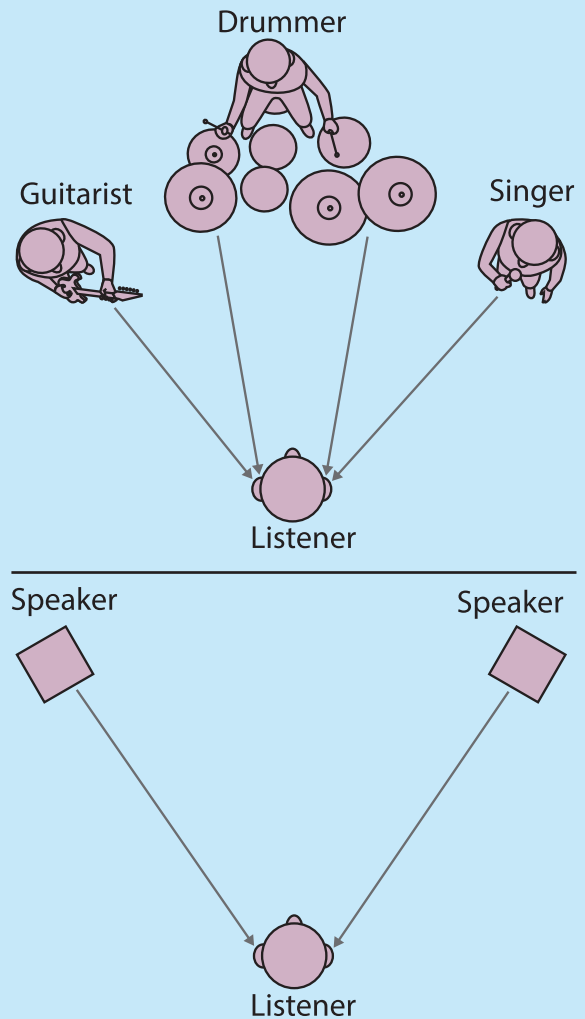
Of course, sound reflects and refracts, too. The waves are blocked and redirected by objects. They interfere with each other and either reinforce each other or cancel each other out in ways that are too complex to fully illustrate visually.



## Giving Direction to Sound in a Space

Speakers and other sound producers can be designed to narrow or broaden the area that receives sound. The relatively flat shape of a typical speaker projects sound waves in a general direction, but this direction is conical—it produces a cone of sound. The farther you are from the speaker, the wider the cone of sound is at your position. The energy is more spread out, meaning the intensity of sound and the volume in your ears will be less than what you would experience closer to the speaker.

If multiple speakers are oriented so their cones of sound meet where the listener is sitting, the listener can experience “left” and “right” components of the sound. Some recordings are done so specific instruments’ sounds will play so the listener feels like they are in the presence of the band or orchestra. Sound for movies is made to shift from side to side with the actions taking place on the screen.



Thoughtful design and placement of speakers can make sounds recorded in stereo seem like the real source of the sound is present in the space. For example, there might be more guitar emitted from the left, and more vocals from the right. Listening with your eyes closed, you're right in front of the stage! You hear the drummer to your right and the singer to your left.

# The Doppler Effect

Let's have  
a little fun!

Turn your head from left to  
right like you are watching a  
motorcycle speed by.

Now do it  
again, and use your voice  
to add the sound effect for the  
motorcycle engine. Did the pitch of  
your engine sound get lower as the  
motorcycle passed you and  
sped away?

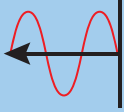
*brrrrrrrrrr!!*

You might not have  
given it much thought,  
but you've probably noticed that  
some sounds seem to change pitch if  
the thing making the sound is either  
approaching you or getting farther  
away. You can observe this when an  
airplane passes  
overhead . . .

. . . or when an  
ambulance with its blaring  
siren drives by.

This phenomenon is the  
Doppler effect.

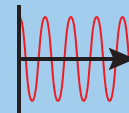
Low frequency



The sound emitted by the sound source isn't actually changing in frequency. That means its pitch should stay the same, right?

Well . . . because the sound source is moving either toward or away from you, the sound waves are either getting bunched up or spread apart between the sound maker and you.

High frequency



As a sound maker moves toward you, it's heading in the same direction as its sound waves that are also moving toward you. Each compression it causes is closer to the compression it just caused—sort of like the sound maker is chasing down its own sound waves.

# A Windy Vancouver Vacation



SCIENCE  
IN HERE

The horn of a large boat will be heard more easily on shore if the wind is blowing in from the ocean—an onshore breeze. If there's an offshore breeze, someone on shore might not hear it at all. The wind seems to carry sounds. What's happening is that wind affects the transmission of sound waves by causing sound waves to bend, or refract, either up or down relative to Earth's surface. If you're downwind from a sound source, sound waves are more likely to reach you on a windy day because sound waves that would normally veer up into the atmosphere instead refract down. If you're upwind from the sound source, the wind bends the sound waves upward, over your head.



Jordan B

We hiked out along the Pacific today. I yelled at Dad and Jalen to turn around and wave for the pic, but they couldn't hear me over the wind and crashing waves. Talk about windy!



SCIENCE  
IN HERE

Wind drives ocean waves to crash on the shoreline, where they emit a rumbling roar. The snapping of windblown clothing adds to the mix of sounds. Wind in the face of a person yelling to these two figures would refract the sound waves upward, never to be heard.



SCIENCE  
IN HERE

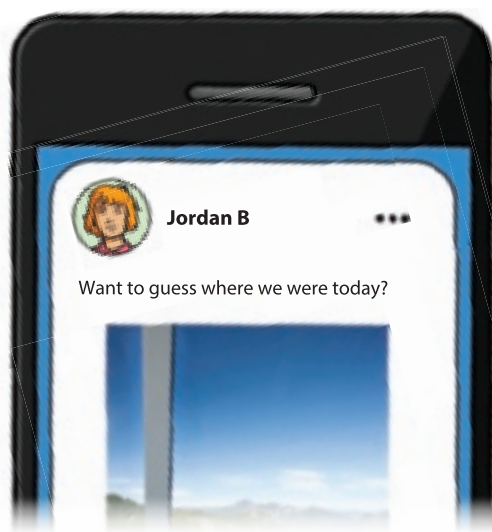
The wind can whistle, howl, roar, hum, and produce many other sounds by interacting with Earth's surface. Wind flowing around branches, taut wires, or ropes can produce buzzing, humming, or whistling sounds. Wind through the leaves of trees can produce high-frequency, high-pitch sounds or gentle rustling. In some places, wind is continuous.



Jordan B

Today we hiked some beautiful trails. Have I mentioned the wind? We could hear the wind whooshing through the trees the whole time. The wind must never let up here. Look what it has done to this tree over time!





## SCIENCE IN HERE

You use moving air to make sounds. Air flowing past your vocal cords causes them to vibrate, and you adjust the pitch by moving your vocal cords within your throat. You can also whistle by holding your lips close together and forcing air through them.

## Connection

Wind is caused by differences in air pressure. Where an air mass is warmed—such as the air over a sunbaked asphalt parking lot—it expands and gets less dense. This warm, expanding air mass rises in the atmosphere. The void left by the rising air mass gets filled by air from a neighboring area on Earth's surface—such as the relatively cool air over a pond next to the parking lot. The horizontal movement of the air mass that fills the void is what we call wind. When differences in temperature and pressure are more extreme, air masses move rapidly—winds get strong and fast.

Some movements of air masses are regular and predictable, producing seasonal, prevailing winds that shape landforms, weather patterns, and life on Earth's surface. For example, along the northern Pacific coast of North America, the prevailing winds during much of the year travel from west to east. This causes ocean swells to crash on windward shores, while the other side of islands, called the lee shore, is sheltered from the wind by the trees and topography of the land.

# A Whisper or a Shriek?

The 18th-century French writer and philosopher Voltaire described the east wind in London in dark terms.

*Black melancholy spreads over the whole nation. Even the animals suffer from it and have a dejected air. Men who are strong enough to preserve their health in this accursed wind at least lose their good humor. Everyone wears a grim expression and is inclined to make desperate decisions.*

European literature holds many examples of poems and stories noting the prevailing winds and their effects on people's moods and behavior.

The sirocco is such a wind that blows into southern Europe from arid North Africa. The sirocco had a depressing effect in ancient lore. It was even believed to impair digestion and kill overindulgent eaters. The wind can be uncomfortably warm and carry dust from the Sahara Desert. Exactly what causes the sirocco or any other wind to make people feel good, bad, calm, or disturbed is hard to determine.

Some effects are direct and physical. For example, the hot sirocco can make someone feel miserably warm, and dust in the wind can irritate the eyes. Other effects of winds are indirect, or based on associations. For example, a sailor might feel good when she hears the wind pick up, because it means she can go sailing. A fisherman who hates to fish in bad weather might feel anxiety or fear as the wind gains strength, especially if his boat is far out to sea with no chance to seek shelter. In these cases, the sound of the wind signals an association in the mind without the wind



"Gust of Wind on a Bridge over the Seine," 1889, Louis Anquetin (1861–1932)

having really produced a direct effect. Its sound can be a beckoning call or a howling warning.

Prevailing winds produce many physical effects, such as windswept trees and driving coastal waves, but the relentless sounds of prevailing winds can also affect organisms that must hear them. For some people, the ceaseless noise of the wind inflicts a maddening torment. Think about how you'd feel if someone stood near you whistling—the same pitch, unstopping, all day and all night, for days or weeks on end!

## Word to Know

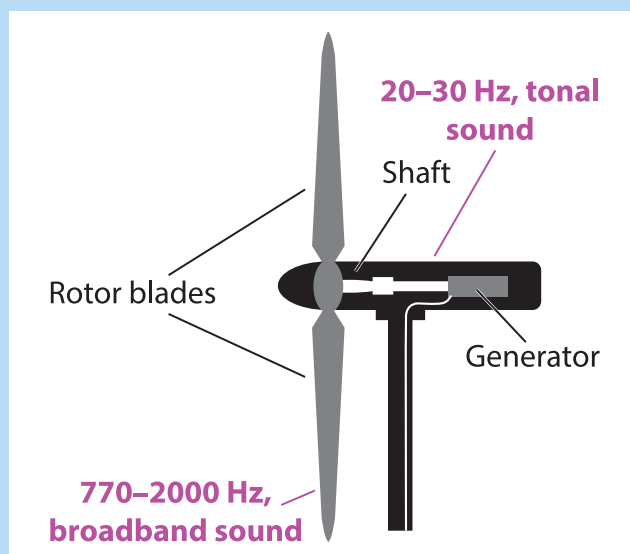
An *association* is a mental connection that a person makes between two or more co-occurring things. An association is not necessarily evidence of a cause-and-effect relationship.

# Wind Turbines

Sails, kites, and windmills are all ancient tools used to harvest mechanical energy from wind. Modern wind turbines convert mechanical energy into electrical energy, but not without some controversy. Some people believe that wind turbines are too noisy, or that infrasonic waves produced by the spinning blades of wind turbines have negative health effects on people. Wind itself can produce infrasounds that are too low for us to hear. For example, a tornado emits infrasound that can be detected miles away before a tornado's audible wind-driven sounds are heard. But is there a direct, causal relationship between wind turbines and human health problems, or is this a modern version of a negative association?

A modern wind turbine usually consists of

- a tall cylindrical tower anchored into the land or the seafloor,
- three blades mounted on a shaft,
- a gearbox in which the mechanical energy of the wind and spinning shaft causes a second shaft to spin at a high rate,
- and an electric generator that converts that spinning shaft's energy into electricity.



The blades of some turbines can be adjusted so the way they receive wind either speeds up or slows down the mechanical action in the gearbox to generate more electricity or less. If the blades spin too slowly, the generator will not generate electricity. If the blades spin too fast, the turbine can be damaged or destroyed.



40 dB

Refrigerator

Wind turbines in residential areas are placed no closer than 300 meters from the nearest house.



Wind turbines make sound in a few ways.

- The mechanical action in the gearbox produces a whirring sound that can have a specific tone.
- The action of the blades through the air, and the way the tower gets in the way of sound waves coming off the blades, produces a whooshing sound.

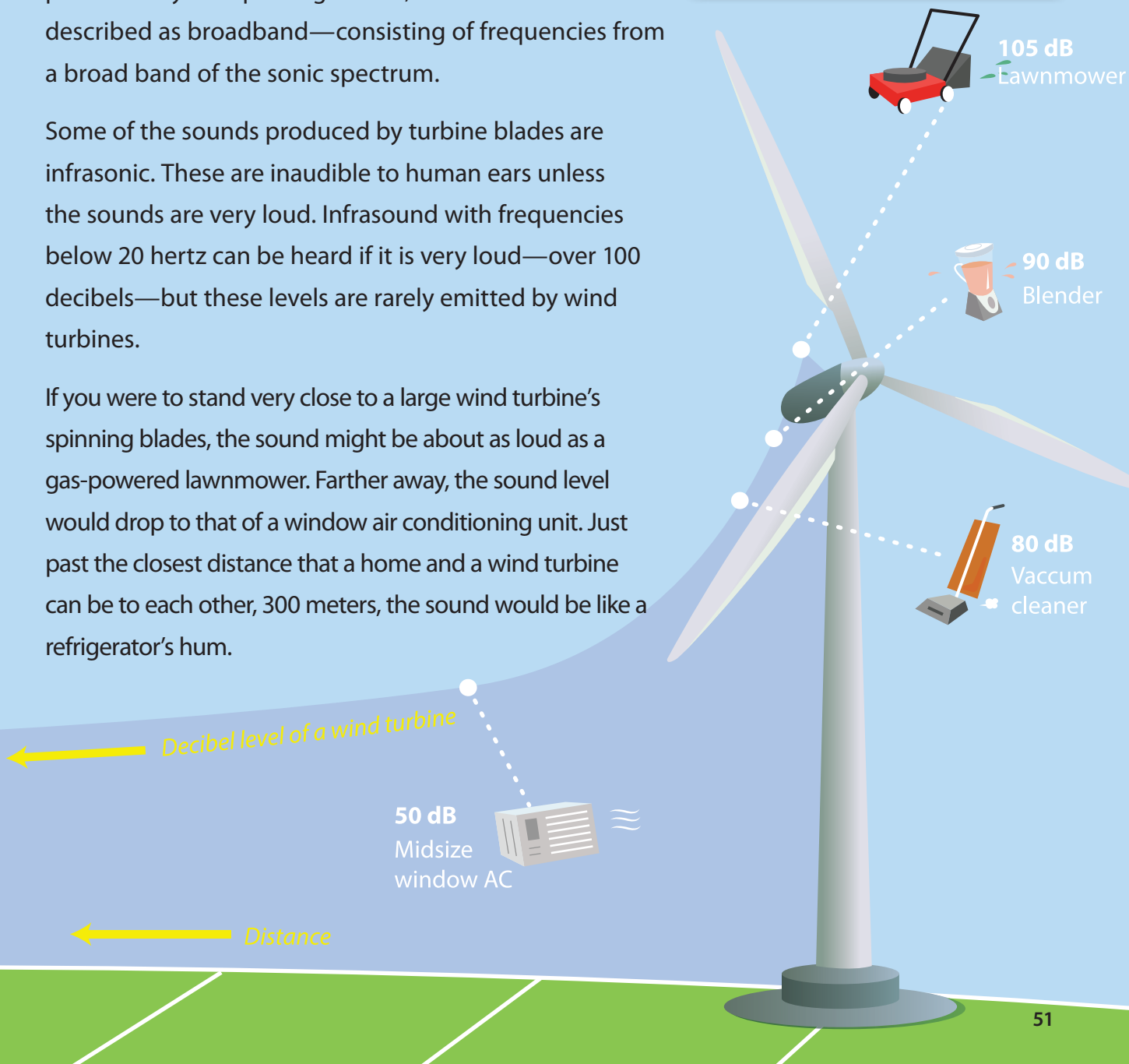
There is no specific tone or pitch to the sounds produced by the spinning blades, so this sound is described as broadband—consisting of frequencies from a broad band of the sonic spectrum.

Some of the sounds produced by turbine blades are infrasonic. These are inaudible to human ears unless the sounds are very loud. Infrasound with frequencies below 20 hertz can be heard if it is very loud—over 100 decibels—but these levels are rarely emitted by wind turbines.

If you were to stand very close to a large wind turbine's spinning blades, the sound might be about as loud as a gas-powered lawnmower. Farther away, the sound level would drop to that of a window air conditioning unit. Just past the closest distance that a home and a wind turbine can be to each other, 300 meters, the sound would be like a refrigerator's hum.

### Consider the Source

This image and data are adapted from a similar diagram produced by a company that manufactures wind turbines. However, the data are specific and independently measurable for verification or dispute. Do these clarifications affect your interpretation of this article?



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SayNoToWindFarm.com

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HOME

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SERVICES

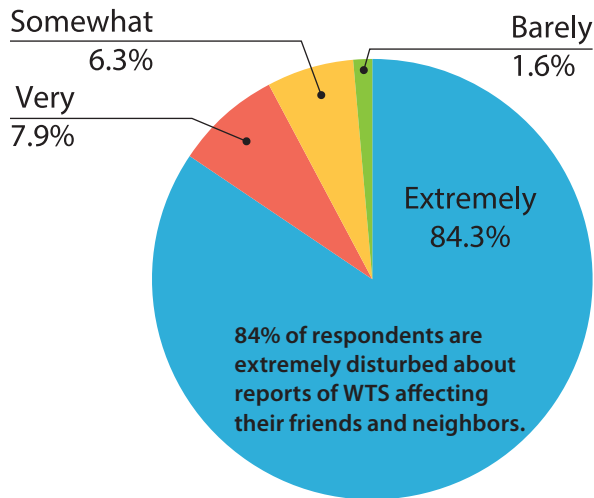
CONTACTS

## A Survey of Wind Turbine Syndrome Victims

by Paul Dauer, MD  
President, Just Say Nay to Whitman Wind Farm

**Introduction** Wind turbine syndrome (WTS) is a medical condition consisting of ailments caused by exposure to sounds emitted by industrial wind turbines. To quantify the impacts of WTS on the residents of Whitman, we conducted a survey of 1,278 households, all of which are within ten miles of the Whitman Wind Farm, which became operational five years ago. The survey consisted of six questions, and respondents could select from one of five responses. Of the households that were sent the survey, 137 responded. The results are shown in the table.

Question	Number of People Who Answered . . .				
	Extremely	Very	Somewhat	Barely	Not at all
1. How disturbed are you by the visual appearance of the wind turbines?	110	22	5	0	0
2. How much has your sleep been disrupted by audible noise from the wind turbines?	17	87	10	20	3
3. How much has your overall level of comfort in your home been adversely affected by infrasonic frequencies emitted by the wind turbines?	8	110	14	5	0
4. How disturbed are you by reports of wind turbine syndrome affecting your friends and neighbors?	107	10	8	2	0
5. How much has your peace of mind been adversely affected by the wind turbines?	120	17	10	0	0
6. How much has the severity of preexisting ailments such as allergies or anxiety been increased by the wind turbines?	38	32	52	7	8
7. Prior to the wind farm’s construction, how concerned were you about its potential effects on your health?	11	100	19	2	5



**Conclusions** The results are clear: WTS is a major problem in Whitman, with the vast majority of those surveyed responding that the turbines are disturbing and disruptive to their health. Before the wind farm was even constructed, most respondents were already concerned about the effects of WTS. Those concerns were well warranted. At least 80 percent of Whitman residents are opposed to this wind farm due to its adverse effects on their health. Enough is enough! It's time for Whitman to shut down the wind farm! Please vote "nay" at the town meeting to any proposed extension of the wind farm's lease.

- Paul Dauer, M.D.

### Dig into Data

What is one problem with how the author acquired responses to his survey?

### Spot the BS

Heads up! There's some **bad science** on this page. Can you detect the problems with this study's design and the author's conclusions?

### Consider the Source

The author of this blog post is a single person holding a medical degree. While he appears to be the president of an organization, its name suggests that he is already invested in an outcome—shutting down the wind farm—that could be more likely if the findings of his survey cast the wind farm in a negative light.

## Wind Turbine Health Impact Study: Report of Independent Expert Panel

### Prepared for:

Whitman Department of Environmental Protection

Whitman Department of Public Health

#### Expert Independent Panel Members:

Jeffrey M. Moore, MD; MMSc

Assistant Professor of Neurology, Whitman University

Division Chief, Sleep Medicine, Whitman General Hospital

Angelica Chunik, PhD; MS Aerospace & Mechanical Engineering

Associate Professor of Mechanical Engineering, Whitman University

William Matsen, PhD

Associate Professor of Environmental Health, Department of Environmental Health,

Beaumont University School of Public Health

Chair, Whitman Board of Health

Lori Hernandez, MD, MPH, FAAP

Vice President for Clinical Affairs, University of the Midwest

Duy Nguyen, ScD Epidemiology; PhD Neuroscience

Associate Professor of Environmental Health and Epidemiology

Department of Environmental Health & Epidemiology, Whitman School of Public Health

The Whitman Department of Environmental Protection (WDEP) in collaboration with the Whitman Department of Public Health (WDPH) convened a panel of independent experts to identify any documented or potential health impacts of risks that may be associated with exposure to wind turbines and, specifically, to facilitate discussion of wind turbines and public health based on scientific findings. The goal of the panel's evaluation and report is to provide a review of the science that explores these concerns and provides useful information to WDEP and WDPH and to local agencies that are often asked to respond to such concerns. The panel consists of five individuals with backgrounds in public health, epidemiology, toxicology, neurology and sleep medicine, neuroscience, and mechanical engineering. In conducting their evaluation, the panel conducted an extensive review of the scientific literature as

well as other reports, popular media, and public comments received by the WDEP. The literature review encompassed 48 peer-reviewed articles as well as seven non-peer-reviewed articles.

### Findings

1. Most literature on human response to wind turbines relates to self-reported "annoyance." This response appears to be a function of a combination of the sound itself, the sight of the turbine, and preexisting attitudes about wind turbine projects.
  - a. There is limited evidence suggesting an association between exposure to wind turbines and annoyance.
  - b. There is insufficient evidence to determine whether there is an association between noise from wind turbines and annoyance

that is distinct from the effects of seeing a wind turbine, and vice versa.

2. There is limited evidence from scientific studies suggesting an association between noise from wind turbines and sleep disruption. It is possible that noise from some wind turbines can cause sleep disruption, but the evidence of causation is unclear or limited.
3. A very loud wind turbine could cause disrupted sleep, particularly in vulnerable populations, at a certain distance, while a very quiet wind turbine would not likely disrupt even the lightest of sleepers at that same distance. But there is not enough evidence to provide particular sound-intensity thresholds at which wind turbines cause sleep disruption. Further study could provide these levels.
4. There is insufficient evidence that the noise from wind turbines is directly (i.e., independent from an effect on annoyance or sleep) causing health problems or disease. This includes infrasound, or sound that might be considered “noise” despite being inaudible except at very high volumes.
5. There is no evidence for a set of health effects caused by or associated with exposure to wind turbines that could be characterized as “wind turbine syndrome.”
6. The weight of the evidence suggests no association between noise from wind turbines and measures of psychological distress or mental health problems.

## Expert Panel Finds Scant Evidence of “Wind Turbine Syndrome”

*Whitman News Editorial Board*

In the wake of a much talked-about blog post by local physician Paul Dauer about “wind turbine syndrome,” a panel of experts released its own report on the associations between wind turbines such as those found at the Whitman Wind Farm and adverse health effects that Dauer and some other prominent anti-wind-energy voices have blamed on wind turbines. The panel reviewed the existing scientific literature and found little evidence to support the idea that wind turbine noise—whether audible sounds or infrasonic waves that can’t be heard but might be felt in some way—poses specific health threats. The panel notes that any sound can be perceived as noise—unwanted, annoying, even anxiety inducing—and wind turbine sounds tend to be difficult to even hear unless the listener is within 400 meters of the spinning blades. The panel suggests that much of the annoyance that some people have for wind turbines seems to stem from their disapproval of their appearance or a preexisting opposition to wind power or renewable energy projects more generally. The panel acknowledges that further study could answer lingering questions and potentially show evidence of the downsides of wind turbines’ sonic output, but for the time being there is no cause for labeling discomfort or disapproval of the Whitman Wind Farm as any kind of “syndrome.”

### Consider the Sources

This article is a simulation with made-up names, but it’s based on a real study. The authors of the report have advanced degrees and positions of authority in fields related to the subject. There are also five of them, and they worked together on a review of other reports written by many other experts. The news report reflects a summary of the findings in the report as from a local newspaper employing professional journalists.

# Glossary

**acoustic, adj.** related to sound

**acoustic soundscape, n.** the collective properties and behaviors of sounds in a given physical environment

**amplify, v.** to increase intensity

**association, n.** a mental connection that a person makes between two or more co-occurring things

**compression, n.** the episode in the transmission of a longitudinal wave during which particles of the medium are bunched closely together

**decibel, n.** a unit for expressing the relative intensity of sounds on a scale from zero for imperceptible sound to about 130 for painfully loud sound

**density, n.** the quantity of mass per unit of volume

**Doppler effect, n.** a change in the observed frequency of waves when a wave source and an observer are moving closer together or farther apart

**elasticity, n.** a measure of how much something can be stretched or bent without breaking and then return to its original shape

**frequency, n.** the number of repetitions of a process over an increment of time; for sound, the rate of oscillations, or cycles of vibration, of a sound source

**geosphere, n.** the system of all the solid, nonliving parts of Earth

**hertz, n.** the quantifiable unit for the frequency of waves, identifying the number of cycles of a vibration of a wave source per second

**hydrosphere, n.** the system of all Earth's water

**infrasonic, adj.** describing sounds with a frequency lower than what human ears can detect

**intensity, n.** the measurable amount of a property; for sound, loudness

**intonation, n.** the accuracy of pitch up and down a string and across all strings of a musical instrument

**longitudinal wave, n.** a wave that vibrates in the direction in which it propagates

**loudness, n.** the quality of the intensity of sound

**media, n.** the collective means of mass communication, including publishing and broadcasting and the presence of publishers and broadcasters on the internet

**medium, n.** an intervening substance through which a force acts or an effect is produced

**modulus of elasticity, n.** is a quantity that measures how resistant a material is to temporarily deforming under stress.

**noise, n.** unwanted, intrusive sound

**noise pollution, n.** unwanted sound that is harmful to the health of organisms

**oppose, v.** to hold a position against something

**pitch, n.** the quality of highness or lowness of a sound, which is a reflection of the wave's frequency

**plane, n.** the flat, two-dimensional region that contains any three points that are not colinear

**rarefaction, n.** the episode in the transmission of a longitudinal wave during which particles of the medium are spaced most far apart

**science literacy, n.** the ability to read, hear, and comprehend information about scientific topics and demonstrate understanding in discussion and through writing

**seismic, adj.** referring to earthquakes or other vibrations of Earth's crust

**shockwave, n.** a high-pressure mechanical wave that pushes particles out of their original positions

**social media, n.** websites and applications that allow users to participate in sharing content on the internet

**solute, n.** the substance in a solution that dissolves in the solvent

**solution, n.** a liquid mixture in which substances are evenly distributed

**solvent, n.** the liquid substance in which a solute dissolves to form a solution

**sound wave, n.** a longitudinal wave that can be perceived by the sense of hearing

**speed of sound, n.** acoustic velocity ( $v$ ); can be calculated in any medium by knowing the medium's density ( $\rho$ ) and its bulk modulus ( $B$ ) (The bulk modulus is a measure of how easy or hard it is to compress or bend the medium.)

**support, n.** in an argument, evidence that bears proof of a position

**surface wave, n.** a mechanical wave that propagates along the boundary between two media

**sustain, v.** in music, to cause a sound to continue

**transverse wave, n.** a wave vibrating perpendicular to the direction it is propagating

**ultrasonic, adj.** describing sounds that have a frequency higher than humans can detect

**vibration, n.** movement of an object or material back and forth past its starting position

**wind turbine, n.** a device that, by rotation of a vaned wheel, converts the kinetic energy of wind to electricity

## Key Sources

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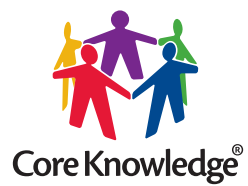
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