How Lightning Works

Lightning is one of the most beautiful displays in nature. It is also one of the most deadly natural phenomena known to man. With bolt temperatures hotter than the surface of the sun and shockwaves beaming out in all directions, lightning is a lesson in physical science and humility.

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Beyond its powerful beauty, lightning presents science with one of its greatest local mysteries: How does it work? It is common knowledge that lightning is generated in electrically charged storm systems, but the method of cloud charging still remains elusive. In this article, we will look at lightning from the inside out so that you can understand this phenomenon.

Lightning begins with a process that's less mysterious: the water cycle. To fully understand how the water cycle works, we must first understand the principles of evaporation and condensation.

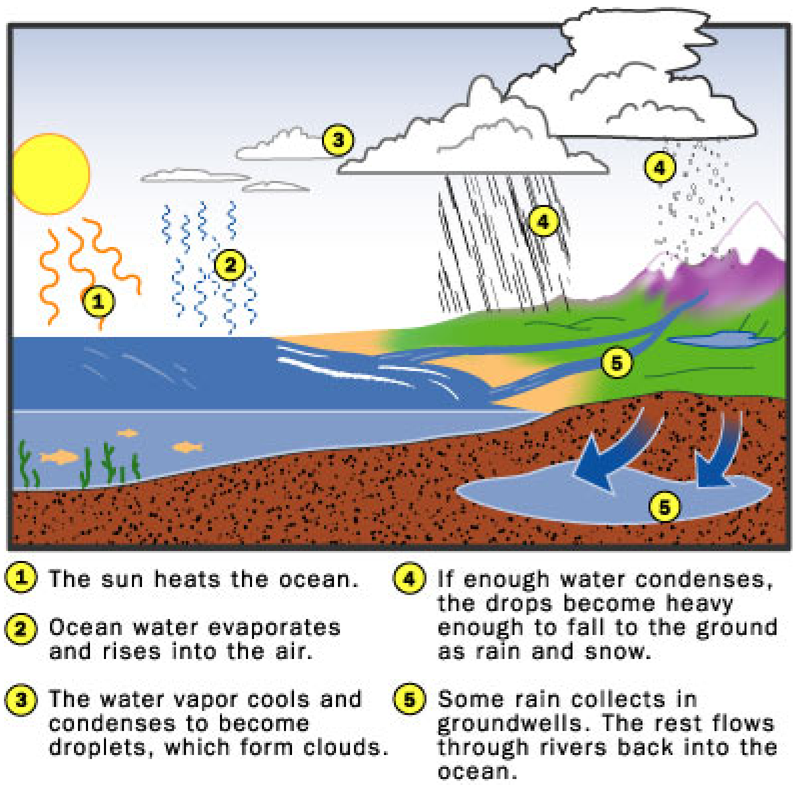
Evaporation is the process by which a liquid absorbs heat and changes to a vapor. A good example is a puddle of water after a rainfall. Why does the puddle dry up? The water in the puddle absorbs heat from the sun and the environment and escapes as a vapor. "Escape" is a good term to use when discussing evaporation. When the liquid is subjected to heat, its molecules move around faster. Some of the molecules may move quickly enough to break away from the surface of the liquid and carry heat away in the form of a vapor or gas. Once free from the constraints of the liquid, the vapor begins to rise into the atmosphere.

Photo courtesy of NASA

More than 1,000 people are struck by lightning annually in the United States. See more lightning pictures.

Condensation is the process by which a vapor or gas loses heat and turns into a liquid. Whenever heat is transferred, it moves from a higher temperature to a lower temperature. A refrigerator uses this concept to cool your food and drinks. It provides a low-temperature environment that absorbs the heat from your beverages and foodstuffs and carries that heat away in what is known as the refrigeration cycle. In this respect, the atmosphere acts like a huge refrigerator to gas and vapors. As the vapors or gases rise, the temperatures in the surrounding air drop lower and lower. Soon, the vapor, which has carried heat away from its "mother" liquid, begins to lose heat to the atmosphere. As it rises to higher altitudes and lower temperatures, eventually enough heat is lost to cause the vapor to condense and return to a liquid state.

Let's now apply these two concepts to the water cycle.



Water or moisture on the earth absorbs heat from the sun and the surroundings. When enough heat has been absorbed, some of the liquid's molecules may have enough energy to escape from the liquid and begin to rise into the atmosphere as a vapor. As the vapor rises higher and higher, the temperature of the surrounding air becomes lower and lower. Eventually, the vapor loses enough heat to the surrounding air to allow it to turn back into a liquid. Earth's gravitational pull then causes the liquid to "fall" back down to the earth, thereby completing the cycle. It should be noted that if the temperatures in the surrounding air are low enough, the vapor can condense and then freeze into snow or sleet. Once again, gravity will claim the frozen forms and they will return to the earth.

In the next section, we'll see what causes electrical storms.

Electrical Storms

In an electrical storm, the **storm clouds are charged** like giant capacitors in the sky. The upper portion of the cloud is positive and the lower portion is negative. How the cloud acquires this charge is still not agreed upon within the scientific community, but the following description provides one plausible explanation.

In the process of the water cycle, moisture can accumulate in the atmosphere. This accumulation is what we see as a cloud. Interestingly, clouds can contain millions upon millions of water droplets and ice suspended in the air. As the process of evaporation and condensation continues, these droplets collide other moisture that is in the process of condensing as it rises. Also, the rising moisture may collide with ice or sleet that is in the process of falling to the earth or located in the lower portion of the cloud. The importance of these **collisions** is that electrons are knocked off of the rising moisture, thus creating a **charge separation**.

The newly knocked-off electrons gather at the lower portion of the cloud, giving it a negative charge. The rising moisture that has just lost an electron carries a positive charge to the top of the cloud. Beyond the collisions, **freezing** plays an important role. As the rising moisture encounters colder temperatures in the upper cloud regions and begins to freeze, the frozen portion becomes negatively charged and the unfrozen droplets become positively charged. At this point, rising air currents have the ability to remove the positively charged droplets from the ice and carry them to the top of the cloud. The remaining frozen portion would likely fall to the lower portion of the cloud or continue on to the ground. Combining the collisions with the freezing, we can begin to understand how a cloud may acquire the extreme charge separation that is required for a lightning strike.

When there is a charge separation in a cloud, there is also an **electric field** that is associated with the separation. Like the cloud, this field is negative in the lower region and positive in the upper region.

The strength or intensity of the electric field is directly related to the amount of charge buildup in the cloud. As the collisions and freezing continue to occur and the charges at the top and bottom of the cloud increase, the electric field becomes more and more intense -- so intense, in fact, that the electrons at the earth's surface are repelled deeper into the earth by the strong negative charge at the lower portion of the cloud. This **repulsion of electrons** causes the earth's surface to acquire a strong positive charge.

All that is needed now is a **conductive path** for the negative cloud bottom to contact the positive earth surface. The strong electric field, being somewhat self-sufficient, creates this path.

We'll look at the next stage of the lightning creation process, air ionization, next.

Air Ionization

The following description is also exactly what occurs when operating a Van de Graaff generator. If you have a hankering to play with lightning, a VDG is definitely the safest way to go and can provide hours of entertainment.

The strong electric field causes the air around the cloud to "**break down**," allowing current to flow in an attempt to neutralize the charge separation. Simply stated, the air breakdown creates a path that short-circuits the cloud/earth as if there were a long metal rod connecting the cloud to the earth. Here's how this breakdown works.

When the electric field becomes very strong (on the order of tens of thousands of volts per inch), conditions are ripe for the air to begin breaking down. The electric field causes the surrounding air to become separated into positive ions and electrons -- the air is **ionized**. Keep in mind that the ionization does not mean that there is more negative charge (electrons) or more positive charge (positive atomic nuclei / positive ions) than before. This ionization only means that the electrons and positive ions are farther apart than they were in their original molecular or atomic structure. Essentially, the electrons have been stripped from the molecular structure of the non-ionized air.

The importance of this separation/stripping is that the electrons are now free to move much more easily than they could before the separation. So this ionized air (also known as **plasma**) is much more conductive than the previous non-ionized air. Incidentally, the ability or freedom of the electrons to move is what makes any material a good conductor of electricity. Often times, metals are referred to as positive atomic nuclei surrounded by a fluid-like cloud of electrons. That makes many metals good conductors of electricity.

These electrons have excellent mobility, allowing for **electrical current** to flow. The ionization of air or gas creates plasma with conductive properties similar to that of metals. Plasma is the tool nature wields to neutralize charge separation in an electric field. Those readers who are familiar with the chemical reaction of fire will recall that **oxidation** plays an important role. Oxidation is the process by which an atom or molecule loses an electron when combined with oxygen. Simply put, the atom or molecule is changed from a lower positive potential to a higher positive potential. Interestingly enough, the process of ionization, which creates plasma, also occurs through the loss of electrons. By this comparison, we can view the ionization process as "burning a path" through the air for the lightning to follow, much like digging a tunnel through a mountain for a train to follow.

After the ionization process, the path between the cloud and the earth begins to form. Learn about step leaders, or paths of ionized air, next.

Lightning Myth #1

The tallest objects in a storm **don't** always get struck by lightning. It's true that taller objects are closer to the clouds, but as discussed previously, lightning can strike the ground at a close distance to a tall object. Taller objects may have a higher possibility of a strike, but where lightning is concerned, the strike path is not predictable.

Step Leaders

Once the ionization process begins and plasma forms, a path is not created instantaneously. In fact, there are usually many separate paths of ionized air stemming from the cloud. These paths are typically referred to as **step leaders**.

Photo courtesy NASA

The step leaders propagate toward the earth in stages, which do not have to result in a straight line to the earth. The air may not ionize equally in all directions. Dust or impurities (any object) in the air may cause the air to break down more easily in one direction, giving a better chance that the step leader will reach the earth faster in that direction. Also, the shape of the electric field can greatly affect the ionization path. This shape depends on the location of the charged particles, which in this case are located at the bottom of the cloud and the earth's surface. If the cloud is parallel to the earth's surface, and the area is small enough that the curvature of the earth is negligible, the two charge locations will behave as two charged parallel plates. The lines of force (**electric flux**) generated by the charge separation will be perpendicular to the cloud and earth.

Flux lines always radiate perpendicularly from the charge surface before moving toward their destination (opposite charge location). Given this knowledge, we can say that if the lower surface of the cloud is not straight, the flux lines will not be uniform. Try this: Draw two points on opposite ends of a basketball. Next, draw a line on the basketball that connects the two points. The curvature of the line is analogous to the flux lines in a non-uniform electric field. The lack of uniform force can cause the step leaders to follow a path that is not a straight line to the earth.

Considering these possibilities, it becomes obvious that there are various factors that affect the direction of the step leader. We are taught that the shortest distance between two points is a straight line; but in the case of electric fields, the lines of force (flux lines) may not follow the shortest distance, as the shortest distance does not always represent the path of least resistance.

So now we have an electrically charged cloud with ever-growing step leaders stretching out toward the earth in stages. These leaders are faintly illuminated in a purplish glow and may sprout other leaders in areas where the original leaders bend or turn. Once begun, the leader will remain until the current flows, regardless of whether or not it is the leader that reaches the ground first. The leader basically has two possibilities: continue to grow in stages of growing plasma or wait patiently in its present plasma condition until another leader hits a target.

The leader that reaches the earth first reaps the rewards of the journey by providing a conductive path between the cloud and the earth. This leader is not the lightning strike; it only **maps out** the course that the strike will follow. The strike is the sudden, massive, flow of electrical current moving from the cloud to the ground.

Before we get ahead of ourselves, we have to consider what is happening with the surface of the earth and objects on the surface. We'll look at positive streamers and what happens when these streamers meet step leaders in the next section.

Positive Streamers and Exploding Air

As the step leaders approach the earth, objects on the surface begin responding to the strong electric field. The objects reach out to the cloud by "growing" **positive streamers**. These streamers also have a purplish color and appear to be more prominent on sharp edges. The human body can and does produce these positive streamers when subjected to a strong electric field such as that of a storm cloud. In actuality, anything on the surface of the earth has the potential to send a streamer. Once produced, the streamers do not continue to grow toward the clouds; bridging the gap is the job of the step leaders as they stage their way down. The streamers wait patiently, stretching upward as the step leaders approach.

Next to occur is the actual **meeting of a step leader and a streamer**. As discussed earlier, the streamer that the step leader reaches is not necessarily the closest streamer to the cloud. It's very common for lightning to strike the ground even though there is a tree or a light pole or any other tall object in the vicinity. The fact that the step leader does not take the path of a straight line allows for this to occur.

After the step leader and the streamer meet, the ionized air (plasma) has completed its journey to the earth, leaving a conductive path from the cloud to the earth. With this path complete, current flows between the earth and the cloud. This discharge of current is nature's way of trying to neutralize the charge separation. The flash we see when this discharge occurs is not the strike -- it is the local effects of the strike.

Any time there is an electrical current, there is also **heat** associated with the current. Since there is an enormous amount of current in a lightning strike, there is also an enormous amount of heat. In fact, a bolt of lightning is hotter than the surface of the sun. This heat is the actual cause of the brilliant white-blue flash that we see.

When a leader and a streamer meet and the current flows (the strike), the air around the strike becomes extremely hot. So hot that it actually **explodes** because the heat causes the air to expand so rapidly. The explosion is soon followed by what we all know as **thunder**.

Thunder is the **shockwave** radiating away from the strike path. When the air heats up, it expands rapidly, creating a compression wave that propagates through the surrounding air. This compression wave manifests itself in the form of a **sound wave**. That does not mean that thunder is harmless. On the contrary, if you are close enough, you can feel the shockwave as it shakes the surroundings. Keep in mind that when a nuclear explosion occurs, typically the most destruction is caused by the energy of the rapidly moving shockwave. In fact, the shockwave that produces the thunder from a lightning strike can most certainly damage structures and people. This danger is more prominent when you are close to the strike, because the shockwave is stronger there and will dampen (decrease) with distance. Physics teaches us that sound travels much slower than light, so we see the flash before we hear the thunder. In air, sound travels roughly 1 mile every 4.5 seconds. Light travels at a blazing 186,000 miles (299,000 kilometers) per second.

Multiple Strikes

You are sitting in your car and you see a flash from a lightning strike. The first thing you notice is that there were many other branches that flashed at the same time as the main strike. Next you notice that the main strike flickers or dims a few more times. The branches that you saw were actually the step leaders that were connected to the leader that made it to its target.

Photo courtesy NOAA Photo Library, NOAA Central Library; OAR/ERL/National Severe Storms Laboratory (NSSL)

Multiple cloud-to-ground and cloud-to-cloud lightning strikes

When the first strike occurs, current flows in an attempt to neutralize the charge separation. This requires that the current associated with the energy in the other step leaders also flows to the ground. The electrons in the other step leaders, being free to move, flow through the leader to the strike path. So when the strike occurs, the other step leaders are providing current and exhibiting the same heat flash characteristics of the actual strike path. After the original stroke occurs, it is usually followed by a series of **secondary strikes**. These strikes follow only the path of the main strike; the other step leaders do not participate in this discharge.

In nature, what we see is often not what we get, and this is definitely the case with the secondary strikes. It is very possible that the main strike can be followed by 30 to 40 secondary strikes. Depending on the time delay between the strikes, we may see what looks like one long-duration main strike, or a main strike followed by other flashes along the path of the main strike. These conditions are easy to understand if we realize that the secondary strike can occur while the flash from the main stroke is still visible. Obviously, this would cause a viewer to think that the main-stroke flash lasted longer than it actually did. By the same token, the secondary strikes may occur after the flash from the main strike ends, making it appear that the main strike is flickering.

Now you know the mechanics of a lightning strike. It's amazing to realize that all of the activity, from the time the ionization begins to the time of the strike, occurs in a fraction of a second. High-speed cameras used to take pictures of lightning have actually caught the positive streamers on film. If you would like to observe this phenomenon in a safe environment, build a Van de Graaff generator and run it in a dark room. As you approach the generator, your fingertips will begin to glow a purplish color like that of a step leader or positive streamer.

Lightning Myth #2

Surge protectors **won't** save your electronics (TV, VCR, PC) if lightning strikes your power line. Surge protectors provide protection for power surges in the line from the power company, but not for lightning. To really guard against strike damage, you need a **lightning arrester**. The arrester uses a gas-filled gap that acts as an open circuit to low potentials, but becomes ionized and conducts at very high potentials. If the lightning hits the line you are protecting, the gas gap will conduct the current safely to ground.

Types of Strikes and Types of Lightning

- **Cloud to ground -** Discussed previously

Photo courtesy NOAA Photo Library, NOAA Central Library; OAR/ERL/National Severe Storms Laboratory (NSSL)

Cloud-to-ground lightning

- **Ground to cloud** - The same as above with the exception that usually a tall, earth-bound object initiates the strike to the cloud

Photo courtesy NASA

Ground-to-cloud lightning

- **Cloud to cloud** - Also the same mechanics as discussed above except the strike travels from one cloud to another

Photo courtesy NOAA Photo Library, NOAA Central Library; OAR/ERL/National Severe Storms Laboratory (NSSL)

Cloud-to-cloud lightning

Types of Lightning

- **Normal lightning** - Discussed previously
- **Sheet lightning** - Normal lightning that is reflected in the clouds
- **Heat lightning** - Normal lightning near the horizon that is reflected by high clouds
- **Ball lightning** - A phenomenon where lightning forms a slow, moving ball that can burn objects in its path before exploding or burning out
- **Red sprite** - A red burst reported to occur above storm clouds and reaching a few miles in length (toward the stratosphere)
- **Blue jet** - A blue, cone-shaped burst that occurs above the center of a storm cloud and moves upward (toward the stratosphere) at a high rate of speed

In the next section, we'll learn about the purpose of lightning rods.

Lightning Rods

Lightning Myth #3

Ben Franklin was **not** struck by lightning. Contrary to popular school teachings, Mr. Franklin was very lucky to survive his experiment. The spark he saw was a product of the kite/key

Lightning rods were originally developed by Benjamin Franklin. A lightning rod is very simple -- it's a pointed metal rod attached to the roof of a building. The rod might be an inch (2 cm) in diameter. It connects to a huge piece of copper or aluminum wire that's also an inch or so in diameter. The wire is connected to a **conductive grid** buried in the ground nearby.

system being in a strong electric field. Had the kite/key actually been struck, Mr. Franklin would surely have been killed. As we all know now, his experiment was extremely dangerous and should not be repeated.

The purpose of lightning rods is often misunderstood. Many people believe that lightning rods "attract" lightning. It is better stated to say that lightning rods provide a **low-resistance path to ground** that can be used to conduct the enormous electrical currents when lightning strikes occur. If lightning strikes, the system attempts to carry the harmful electrical current away from the structure and safely to ground. The system has the ability to handle the enormous electrical current associated with the strike. If the strike contacts a material that is not a good conductor, the material will suffer massive heat damage. The lightning-rod system is an excellent conductor and thus allows the current to flow to ground without causing any heat damage.

Lightning can "**jump around**" when it strikes. This "jumping" is associated with the electrical potential of the strike target with respect to the earth's potential. The lightning can strike and then "seek" a path of least resistance by jumping around to nearby objects that provide a better path to ground. If the strike occurs near the lightning-rod system, the system will have a very low-resistance path and can then receive a "jump," diverting the strike current to ground before it can do any more damage.

As you can see, the purpose of the lightning rod is not to attract lightning -- it merely provides a safe option for the lightning strike to choose. This may sound a little picky, but it's not if you consider that the lightning rods only become relevant when a strike occurs or immediately after a strike occurs. Regardless of whether or not a lightning-rod system is present, the strike will still occur.

If the structure that you are attempting to protect is out in an open, flat area, you often create a lightning protection system that uses a very tall lightning rod. This rod should be taller than the structure. If the area finds itself in a strong electric field, the tall rod can begin sending up positive streamers in an attempt to dissipate the electric field. While it is not a given that the rod will always conduct the lightning discharged in the immediate area, it does have a better possibility than the structure. Again, the goal is to provide a low-resistance path to ground in an area that has the possibility to receive a strike. This possibility arises from the strength of the electric field generated by the storm clouds.

Lightning Safety

More than 1,000 people get struck by lightning every year in the United States, and more than 100 of them die as a result of the strike. Lightning is not something to toy with.

If you are caught outside in a storm, always look for appropriate shelter. Do not take any chances -- lightning can use you as a path to the earth just as easily as it can use any other object. Appropriate shelter would be a building or a car (see the "lightning myth" sidebar at the bottom of the page to find out why). If you do not have anywhere to go, then you should avoid taking shelter under trees. Trees attract lightning. Put your feet as close together as possible and crouch down with your head as low as possible without touching the ground.

Never lay down on the ground. After lightning strikes the ground, there is an electric potential that radiates outward from the point of contact. If your body is in this area, current can flow through you. You never want the current to have the ability to pass through your body. This could cause cardiac arrest, not to mention other organ damage and burns. By making your body as low to the ground as possible and minimizing the amount of your body in contact with the ground, you can lower the possibility of a lightning-related injury. If a strike were to occur near you, the current would have a much more difficult time flowing through your body in this position.

If you are indoors, stay off the phone. If you must call someone, use a cordless phone or cell phone. If lightning strikes the phone line, the strike will travel to every phone on the line (and potentially to you if you are holding the phone).

Stay away from plumbing pipes (bath tub, shower). Lightning has the ability to strike a house or near a house and impart an electrical charge to the metal pipes used for plumbing. This threat is not as great as it used to be, because PVC (polyvinyl chloride) is often used for indoor plumbing these days. If you are not sure what your pipes are made of, wait it out.

Lightning Myth #4

Rubber tires **aren't** why you're safe in a car during a lightning storm. In strong electric fields, rubber tires actually become more conductive than insulating. You're safe in a car because the lightning will travel around the surface of the vehicle and then go to ground. This occurs because the vehicle acts like a **Faraday cage**. Michael Faraday, a British physicist, discovered that a metal cage would shield objects within the cage when a high potential discharge hit the cage. The metal, being a good conductor, would direct the current around the objects and discharge it safely to the ground. This process of shielding is widely used today to protect the electrostatic sensitive integrated circuits in the electronics world.

For more information on lightning and related topics, check out the links on the next page.

Lightning Pictures

Lightning is an impressive force of nature, as beautiful as it is dangerous.

Cloud-to-ground lightning is what most people think of as a lightning strike.

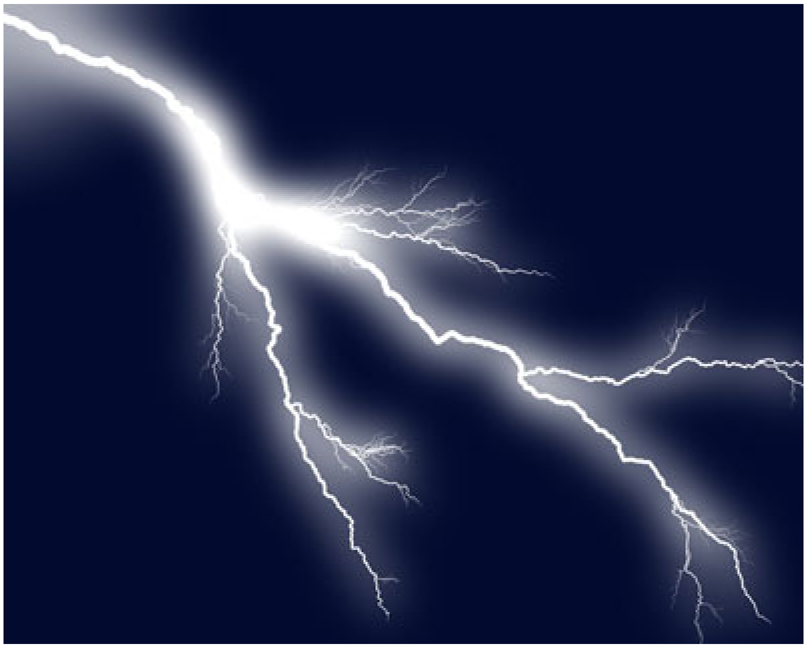
Two kinds of electricity: wild in lightning and harnessed to power a streetlight.

To avoid being struck by lightning, always seek shelter during an active electrical storm.

Flashes of lightning against clouds creates an otherworldly effect.

Looking at this bolt that resembles a dragon, it's easy to see why lightning was once viewed as supernatural.

Water is an excellent conductor, so it's wise to stay away from lakes and pools during a lightning storm.



The brilliant white-blue flash of lightning is caused by its extreme heat. A lightning bolt is hotter than the surface of the sun.

The tallest objects in a storm don't always get struck by lightning. Lightning can strike the ground at a close distance to a tall object.

The first strike of lightning is generally followed by a series of secondary strikes, all within a split second.

See more lightning pictures.

Can you calculate how far away lightning struck by how long it takes for the thunder to arrive?

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Science Videos

Sound travels through air at "**the speed of sound**." Officially, the speed of sound is **331.3 meters per second** (1,087 feet per second) in dry air at 0 degrees Celsius (32 degrees Fahrenheit). At a temperature like 28 degrees C (82 degrees F), the speed is 346 meters per second.

As you can see, the speed of sound changes depending on the **temperature** and the **humidity**; but if you want a round number, then something like 350 meters per second and 1,200 feet per second are reasonable numbers to use. So sound travels 1 kilometer in roughly 3 seconds and 1 mile in roughly 5 seconds.

When you see the **flash** of a lightning bolt, you can start counting seconds and then divide to see how far away the lightning struck. If it takes 10 seconds for the thunder to roll in, the lightning struck about 2 miles or 3 kilometers away.

Can I get struck by lightning when I'm indoors?

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2. Lots More Information

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Over 1,000 people get struck by lightning every year in the United States, and over 100 of them die as a result of the strike. Lightning is a very dangerous force that, yes, can even reach you indoors if you're in contact with the telephone or plumbing.

Pete Turner/Getty Images

Lightning has the ability to strike a house or near a house and impart an electrical charge to the metal pipes used for plumbing.

If lightning strikes the phone line outside your house, the strike will travel to every phone on the line -- and potentially to you if you are holding the phone. So, if you are indoors during a lightning storm, stay off the phone. If you must call someone, use a cordless or cell phone -- that way, you're not in contact with any wires that run outdoors.

Stay away from plumbing pipes like your bath tub or shower, as well. Lightning has the ability to strike a house or near a house and impart an electrical charge to the metal pipes used for plumbing. If you're touching those pipes or anything connected to those pipes, that electrical charge has a path to you. This threat is not as great as it used to be, because PVC (polyvinyl chloride) is often used for indoor plumbing these days. If you are not sure what your pipes are made of, wait it out.

And while you're at it, switch off your appliances and electronics before the storm hits. Such devices as your computer, television and air conditioner all provide potential pathways between the lightning and you.

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