Technology Brief 2
Voltage: How Big Is Big?

Electrical voltage plays a central role in all of our electrical circuits, our bodies, and many other effects seen in the natural world. **Table TT2-1** gives some perspective on really little and really big voltages.

Table TT2-1: A wide range of voltage levels.

Bird standing on a power line (foot to foot)	10 mV
Neuron action potential	55 mV
Cardiac action potential	100 mV
AA battery	1.5 V
TTL digital logic gates	5 V
Residential electricity (US)	110 V / 220 V
High voltage lines	110 kV +
Static electricity	20 to 25 kV
Lightning	1 billion volts

Big Voltages: Lightning

Lightning begins with clouds and the water cycle. Storm clouds have tremendous amounts of turbulent air (updrafts and downdrafts). This results in a thunderhead, a cumulonimbus cloud that has the typical vertical shape we all associate with a storm coming on. These clouds can build quite suddenly from otherwise mild skies, thus bringing on the classic afternoon thunderstorm. Freezing and collisions of the water particles in the cloud break some of the electrons away from the particles, making the storm clouds positively charged at the top and negatively charged at the bottom (**Fig. TF2-1**). This creates a voltage difference, similar to a battery, with values around a billion volts!

Like a battery, these charges cannot just travel through the air, because air is a good insulator. Normally, a wire or other metal conductor would be needed in order to carry the current from a battery. Not so with lightning. The separation of charges (voltage difference) creates an ***electric field***. *When the electric field is high*

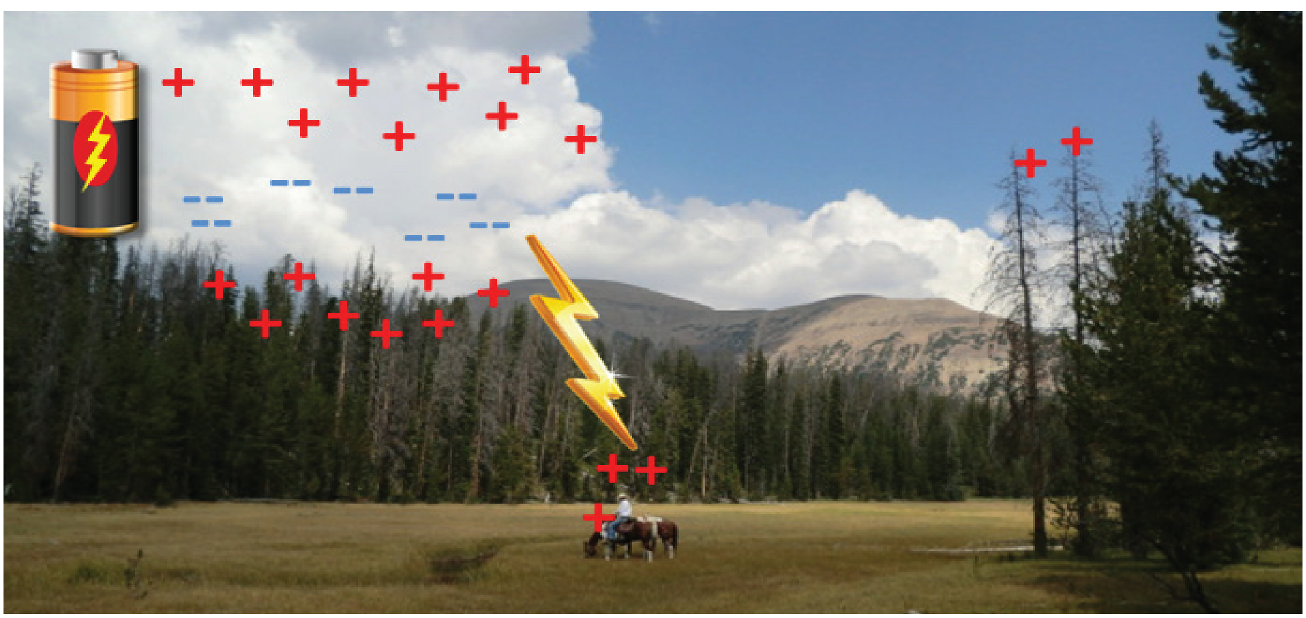


Figure TF2-1: Turbulent air causes negative charges to build up on the bottom of cumulonimbus clouds, separated from the positive charges on the top. The negative charges attract positive charges from the Earth, which move to the top of tall objects. A lightning strike can occur between the negative cloud and positive Earth charges.

enough (around 3 MV/m), the air breaks down and partially ionizes. This means it changes from an insulator (that cannot conduct electricity) to a conductor (that can). The air breakdown creates ozone, and the “fresh air” smell associated with lightning storms. The path of ionized air is called a step leader. The negative charges on the bottom of the cloud begin drawing positive charge towards the Earth’s surface. The positive charges are pulled as close to the negative cloud charges as possible. They concentrate on the tops of things that are tall, like trees, golfers, farmers on their tractors, and hikers in the mountains. These positive charges create streamers, reaching towards the negative cloud charges. When a positive streamer and a negative step leader meet, they can form a complete path (like a wire) for lightning to travel from the cloud to the ground (other types of lightning follow a slightly different process). Silently, the lightning strike occurs.

But the ionized air is only a partial conductor. When the current of lightning passes through the resistive air, the air heats up and expands so much and so quickly that it causes a shock wave that produces a sound wave to radiate away from the strike path. That’s thunder.

What should you do if a lightning storm approaches? First, go indoors if you can, and stay away from water lines and electrical appliances. Unplug sensitive electronics. Lightning may strike the building, but the currents will pass through the walls or the electrical system, to ground. If you are outdoors, avoid high places, move off the ridges and into draws and lowlands.

Also stay away from high, pointy things (such as tall trees, flag poles, and raised golf clubs). Objects that are pointy will concentrate the charge (and create a stronger streamer) than things that are smooth and rounded. Lightning rods use this principle to protect buildings and structures. The lightning rod produces a much stronger streamer than the rest of the building, so it is more likely to be struck. The current from the lightning bolt can then (hopefully safely) go down the cable to a ground rod buried under the building. **Figure TF2-2** shows an example on the old rock church at Sleepy Hollow. Every chimney and the weather vane on the steeple has a separate lightning rod and cable. People and animals also make good lightning rods. We are about 2/3 salt water, which is a pretty good conductor, and we are tall and pointy, similar to a lightning rod. Thus, people (and other animals) are very capable of sending up positive streamers that attract negative step leaders. Consider your profile if you are golfing, hiking, horseback riding, riding on a tractor or mower. In all cases, you are the tallest thing around. Golfers and farmers on tractors have some of the highest incidences of lightning strikes. So, avoid being a lightning rod. Avoid being the tallest thing around.

Figure TF2-2: Lightning rod and grounding cable on Old Rock Church at Sleepy Hollow, New York. The lightning rod attracts the strike by concentrating charges at its tip. The cable shunts the current to ground, carrying it on the outside of the (rock) church, rather than on the inside where materials (wood, plaster, etc.) are more flammable. The cable is large enough in diameter to carry the current without burning, although it will still be hot to the touch after a lightning strike.

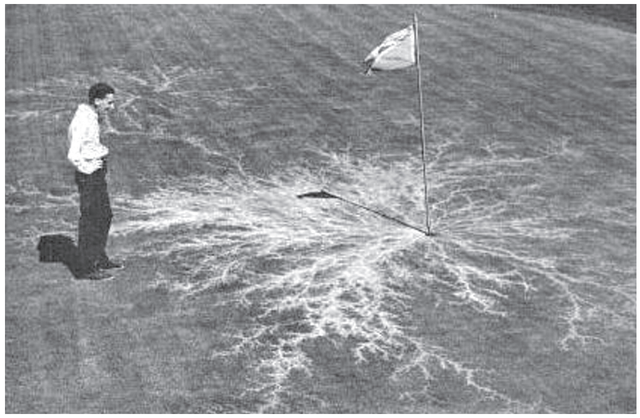


Figure TF2-3: Radial, dendritic pattern of scorched grass caused by lightning strike of golf course pin flag. [From *National Geographic*, Colton, 1950.]

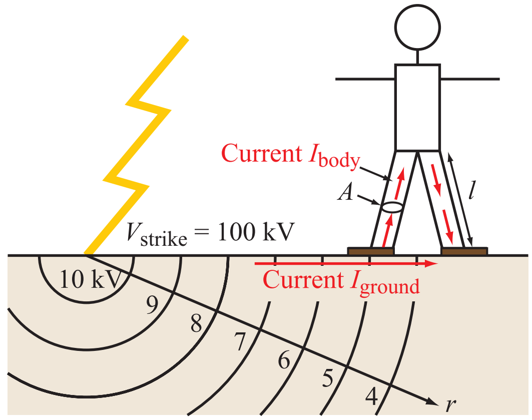
The most common cause of lightning injury is not a direct strike, but the ground current. When lightning strikes, it brings negative charges from the cloud down to the positively charged Earth. It then spreads those charges until all of the negative lightning charges are combined with positive Earth charges. Some of the charge spreads over the surface of the ground. (See for example the pattern on the ground by the golf flag in **Fig. TF2-3**.) Some current also penetrates deeper into the Earth. The charges spreading on the surface of the Earth are called ground currents, and they are real currents that can cause injury.

Electrical Safety

Electrical safety is a function of the current that goes through your body. From Ohm's Law we know that $I = V/R$, so the current depends on the voltage and resistance. The voltage depends on the source (see **Table TT2-1**). The resistance depends on how you connect to the voltage source—did you touch it with a dry finger, a sweaty shoulder, or were you walking across a wet field when lightning produced a ground current? Were you wearing rubber soled tennis shoes or golf shoes with metal cleats?

The minimum current a human can feel (the ***threshold of sensation***) depends on the frequency and whether the current is ac, dc, or pulsed. Most people can feel 5 mA at dc or 1 mA at household 60 Hz ac. This is generally considered benign, although most people are not comfortable with the sensation. You will feel a mildly painful current if you briefly touch a 9 V battery to your tongue. A more dangerous condition occurs around 10 mA when the muscles lock up and cannot release an electrified object. This is the "let go threshold" and is a criterion in electrical regulations for ***shock hazard***. Additional risk is associated with sensitive organs, particularly those that are controlled by electrical signals such as the heart and brain. As little as 10 μV applied directly to the heart can cause ***fibrillation***. Typical voltages used to deliberately pace the heart with internal defibrillators or pace makers are -100 to 35 mV. You might have noticed a change in units from current to voltage in this description. Some disciplines use voltage, others use current, mainly due to what they find easiest to measure. We know they are related via Ohm's law, although more information is always needed to define the resistance and the specific conditions under which it is assumed, calculated, or measured. The ANSI/IEEE Standard 80-1986 uses 1 kΩ for the body resistance. Adding dry shoes and standing on dry ground, the total resistance is 5–10 kΩ.

Current flow requires two contact points (a node where the current enters the body and a node where it leaves). The resistance R is made up of a combination of series and parallel resistances between these two nodes. For example, in the case of lightning-induced ground current, the current will typically enter one foot,



$$\text{Voltage} = \frac{V_{\text{strike}}}{\frac{1}{2}\left(\frac{4}{3}\pi r^3\right)}$$

Figure TF2-4: Current path from a lightning strike.

travel through the body, and exit through the other foot. The total resistance will be the sum of resistance from one shoe (R_{shoe}), the series and parallel resistances as the current travels through the body to the other foot (R_{body}), and the resistance of the other shoe (R_{shoe}). The total resistance $R = R_{\text{shoe}} + R_{\text{body}} + R_{\text{shoe}}$ (see **Fig. TF2-4**). There is another resistance here too, the resistance through the ground, which is parallel to R, and it is controlled by soil type and moisture content.

The resistance between the source of the current and the body is often called the ***contact resistance*** (in this case, it is R_{shoe}). In applications where you want to maximize the current in the body or other object (such as reading the voltages from the heart with an electromyogram (EMG)), you want to minimize the contact resistance. This is often done by using large, conducting electrodes to connect to the body, and placing conductive gels between the electrode and the body. In applications where you want to minimize the current in the body (such as protection from electric shock), you want to maximize the contact resistance. This can be done by minimizing the surface area of the body in contact with the current source and making sure the contact area is dry and insulating (for instance wearing rubber-soled shoes).

Electrical engineers protect people, buildings, circuits, etc., in several ways. Preventing contact between the source and a person or animal can be done with locked buildings and fences, warning signs, and insulators as simple as rubber handles on tools and fiberglass (rather than aluminum) ladders. Circuit protection devices such as circuit breakers and fuses limit the current by tripping (opening the circuit up) if the current exceeds their maximum rating. In circuit breakers, a bimetal junction heats up when current passes through the element. One metal heats up faster than the other, bending/breaking away and disconnecting the circuit. Fuses use a thin metal filament that burns away when its current rating is exceeded, opening the circuit. Current limiting resistors in series with other circuit elements such as potentiometers prevent the resistance from going to zero, thereby preventing large currents. Current limiting devices are effective within moderate ranges of voltage, but very high voltages such as lightning can simply “jump the gaps” even when the circuit is opened up. Rather than trying to simply “stop” the current, protection from very high currents typically relies on shunting the current away from more sensitive circuits, sending it straight to ground. The lightning rod/cable system is one example of this. The cable is a short circuit straight to ground and is sized large enough to carry these very large currents without melting. Other lightning protection circuits use bypass capacitors or various types of filters in parallel with the circuit being protected.