# Section 10.3

# Telephones

*Telephones allow you to talk to friends over great distances by measuring the sound of one person's voice and recreating that sound in another person's ear. Telephones perform this task accurately and cheaply by representing sound as a current flowing through two wires. In fact, these two wires are the only wires that run from the telephone company to your telephone, a remarkable achievement given that the two wires have at least five independent jobs. First, they supply electric power to simple telephones. Second, they convey sound information from the distant talker to your telephone's speaker. Third, they convey sound information from your telephone's microphone to the distant listener. Fourth, they tell the telephone company what number you are dialing. And fifth, they carry the signal that makes your telephone ring when someone is calling you.*

***Questions to Think About:*** *How does talking into the mouthpiece affect the electric current flowing through your telephone and your friend's telephone? What carries sound from your friend's voice to your ear? Why must your telephone distinguish between sounds you make and sounds made at other telephones? What happens when several telephones in your home are active at once? How does the telephone company know what number you dialed or when you have answered the telephone?*

***Experiments to Do:*** *There are many experiments you can do with a telephone. When you're talking on the telephone you should notice that people on other telephones hear your voice through their earpieces but you don't. Something inside your telephone prevents it from recreating your own voice in your earpiece. Listen to the sounds of a touch-tone telephone being dialed. Each sound contains two separate tones. On older telephones, you can hear just one of the tones by pressing two buttons at once. Another trick you can do with telephone systems that allow rotary dialing is to dial by rapidly tapping the switchhook (the button that hangs up the telephone). If you hang the telephone up rapidly 7 times and then pause, you will have dialed a 7. A rotary dialer automatically does this same process of hanging up repeatedly.*

## The Telephone System

It's remarkable that a telephone has only two wires connecting it to the telephone company (Fig. 10.3.1). A table lamp is connected to the power company by two wires and the only thing it can do is light up. A telephone can convey your voice to a friend, it can convey your friend's voice to you, it can choose which friend you're talking to, and it can even tell you when someone is calling. How it manages to do all of these tasks with only two wires is an interesting story and the topic of this section.

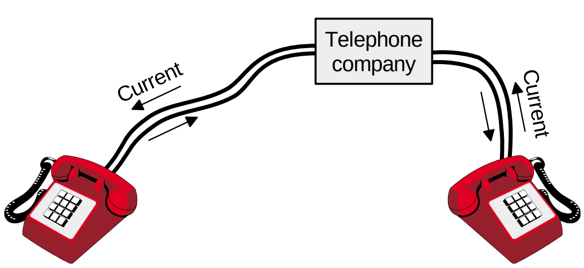


Fig. 10.3.1 - Two telephones are connected to one another through the telephone company. Despite its simple, two-wire connection to the telephone company, each telephone is able to perform many separate functions.

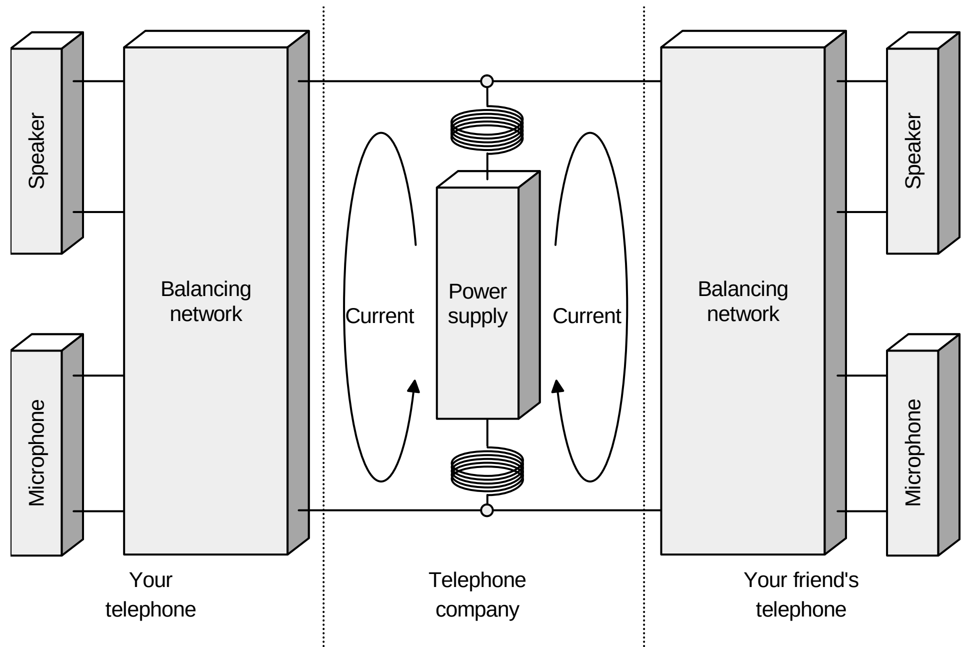


Fig. 10.3.2 - A telephone system with two connected telephones. The telephone company pumps a steady current through both telephones. As someone talks, their microphone alters the pattern of current flow and their voice is heard in the speakers.

Figure 10.3.2 is a block diagram of the telephone system that allows two people to talk to one another by telephone. Each telephone is connected to a pair of wires that meet at the telephone company. If there were a third telephone present, either at the same site as one of these two telephones or at a third site for a conference call, then it would just share those same two wires again.

This arrangement for the telephones, in which they share a current among them, is called a parallel circuit. An example of a simple parallel circuit appears in Fig. 10.3.3*a*. In a parallel circuit, the current is shared between two or more devices and they all experience the same voltage drop. How that current is shared depends on their individual resistances. A device with a low resistance receives more of the current than one with a high resistance. In a series circuit (Fig. 10.3.3*b*), the current flows sequentially through the devices and each experiences its own voltage drop. Which one experiences the largest voltage drop also depends on their individual resistances. A device with a low resistance experiences a smaller voltage drop than one with a high resistance.

Power for the telephone conversation is provided by the telephone company, which sends current through both telephones in parallel and receives that current back from both telephones. Because the telephones share the current, when one telephone begins to carry more current, the other begins to carry less.

To make the telephone system work, the telephone company sends a steady current through the telephones. No matter what happens to those telephones during the conversation, the total current passing through them remains the same.

The telephone company maintains this constant current with the help of the coils shown in Fig. 10.3.2. Each coil consists of an insulated wire wound around a soft iron core (Fig. 10.3.4). When current flows through the wire coil, the core is magnetized and contains magnetostatic potential energy. This potential energy allows the coil to respond to changes in current. If the current through the coil decreases, the magnetic field begins to decrease and creates an electric field. This electric field does work on the current, acting to increase it. If the current through the coil increases, the magnetic field begins to increase and this, too, creates an electric field. Now the electric field does negative work on the current, acting to decrease it.

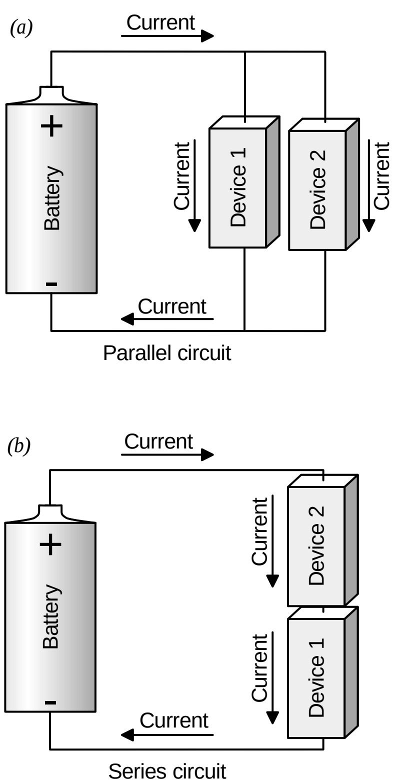


Fig. 10.3.3 - (*a*) In a parallel circuit, the current is shared by two devices. (*b*) In a series circuit, all of the current flows first through one device and then through the second.

The coil thus opposes changes in current and naturally regulates its flow. It's relatively hard to start or stop the current passing through such a coil. This sort of coil is called an **inductor**. The two inductors at the telephone company make sure that the total current flowing through the telephones doesn't change.

However, the coils don't stop one telephone from changing its share of the current. When you talk into the mouthpiece, the sound of your voice changes the amount of current flowing through your telephone. Whenever the current through your telephone increases, the current through your friend's telephone decreases and vice versa. These changes in current through your friend's telephone cause it to reproduce the sound of your voice in your friend's ear.

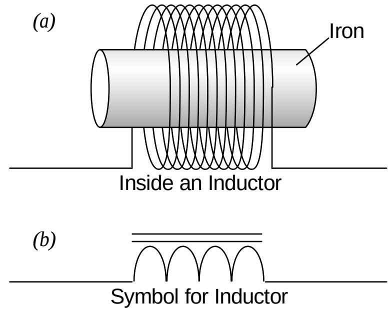


Fig. 10.3.4 - (*a*) An inductor is a coil of wire that often contains a core of soft magnetic material such as iron. (*b*) In a schematic diagram, an inductor is represented by this symbol.

**CHECK YOUR UNDERSTANDING #1: Watch the Sparks Fly**

Many devices, including electric motors, contain electromagnets. Why is it that when you turn off an electric motor, the switch often sparks as it breaks the connection; as though the current doesn't want to stop flowing?

# Telephone Microphones

A basic telephone consists of a microphone, a speaker, and a simple electronic network that improves the behavior of the telephone. It also has a system for dialing and a bell to announce an incoming call. Modern telephones often contain sophisticated electronic devices, such as audio amplifiers, radio transmitters and receivers, lights, and audio recorders, but the basic concepts are still the same.

When you talk into the microphone, it changes the amount of current flowing through the telephone. In older telephones, the microphone contains a small canister of carbon granules between two metal sheets (Fig. 10.3.5). Since carbon conducts electricity somewhat, the microphone is a resistor. Current from one metal sheet flows to the other sheet over a circuitous path through the granules.

The more tightly packed the carbon granules, the more they touch one another and the more direct the current path becomes. Compression causes the carbon microphone's electric resistance to decrease. Expansion causes it to increase. As you talk into the microphone, the air pressure fluctuations in your voice alternately compress and expand the granules and make the resistance of the microphone fluctuate up and down. Because the microphone is connected between the two telephone wires, this fluctuating resistance causes a fluctuating current to flow through the telephone. Since all of the telephones in the parallel circuit share the same current, talking into the microphone of one telephone changes the currents flowing through each of the other telephones.

In more modern telephones, more sophisticated electronic microphones and amplifiers have replaced the carbon microphone. There are literally dozens of types of microphones but the most popular one for telephones is the electret microphone. An **electret** is a thin insulating film that has charges permanently trapped in its surfaces. One surface is positively charged and the other surface is negatively charged—the film is electrically polarized. Although this charge separation slowly disappears, it takes hundreds or even thousands of years to vanish.

In an electret microphone, the electret film is drawn taut like the head of a drum and is suspended just above a metal surface. As you talk into the microphone, pressure fluctuations in the air distort the electret film up and down, and it moves toward and away from the metal surface below it. Charges in the metal surface experience fluctuating forces as the polarized electret moves back and forth. As a result of these forces, current flows alternately toward and away from the metal surface through a wire that touches it.

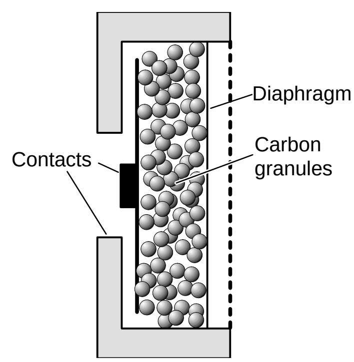


Fig. 10.3.5 - The carbon microphone of an older telephone contains carbon granules between two metal sheets. One of the sheets is a thin diaphragm that pushes and pulls on the granules as you talk and causes the microphone's resistance to fluctuate up and down.

The fluctuating current from the metal surface is extremely small, so the electret microphone includes a built-in preamplifier. This preamplifier is usually a single semiconductor chip containing all of the transistors, resistors, and capacitors needed to form a complete amplifier. Because it contains many components, already interconnected to form an entire electronic device, this chip is called an **integrated circuit**. The chip begins as a wafer of pure silicon, which is chemically modified to create n-type and p-type regions, oxidized to create insulating quartz regions, and coated with aluminum to create microscopic wires and surfaces. The individual components are created and shaped using photolithographic techniques.

Electret microphones can be extremely small, often smaller than a shirt button. A telephone using an electret microphone can be much more compact than one using a carbon microphone. However, a telephone with an electret microphone must still make sure that talking into the microphone causes the current flowing through the telephone to vary. That fluctuating current is what allows all the other telephones to reproduce the sound.

| **CHECK YOUR UNDERSTANDING #2: Many Pieces are Better than One** |
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| Why does a carbon microphone use carbon granules rather than a solid piece of carbon? |

## Telephone Speakers and the Balancing Network

When the current through the telephone changes, the telephone's speaker creates sound. The speaker is a device that converts an electric current into pressure fluctuations in the air. A conventional speaker pushes and pulls on the air with a paper or plastic membrane, usually in the form of a cone (Fig. 10.3.6). The cone is driven in and out by the electric current through the telephone. Of course, this sound generation process requires a conversion of electric power into mechanical power. The speaker performs this conversion using electromagnets.

The speaker contains a permanent magnet that's fixed to the back of the speaker so that it's immobile. It also has a mobile coil of wire that becomes a magnet when current flows through it. The permanent magnet and the coil are arranged so that they attract one another if current flows one direction through the coil and repel one another if the current is reversed. When an alternating current flows back and forth through the coil, the coil is alternately attracted to the permanent magnet and repelled from it.

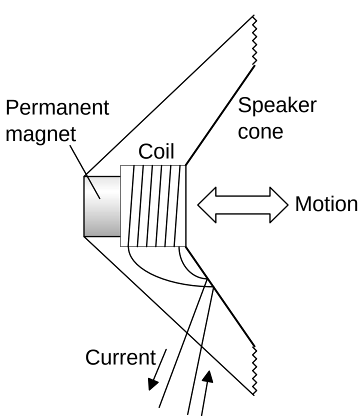


Fig. 10.3.6 - A speaker converts electric power into sound by moving a paper or plastic membrane. This speaker cone is driven back and forth by magnetic forces between a fixed permanent magnet and a current-carrying coil of wire on the cone.

The speaker coil is attached to the speaker cone so that the two move together. The cone is loosely supported by the speaker's frame only at its periphery. The coil and cone have very little mass so that they accelerate in and out very easily. Their main resistance to motion is the air itself. As the cone moves out, it compresses the air in front of it and as it moves in, it rarefies the air in front of it. When it moves in and out rapidly, it produces sound.

The speaker does a good job of converting an electric current representing sound into actual sound. The compressions and rarefactions of the air that it produces are very closely related to the current fluctuations passing through it. Unfortunately, speakers aren't perfect. A small speaker can follow the electric current very well, even at quite high frequencies. But it has difficulty moving the large amounts of air needed to create reasonable volume at very low frequencies. A large speaker can move enough air to have decent volume at low frequencies but it's too massive to respond quickly enough to produce high frequencies. A telephone can live with these limitations and uses a single small speaker to reproduce sound. However good audio speaker systems employ several different speakers of different sizes so that they can share the task of producing the sound. Small speakers are used to produce high frequencies and large speakers are used to produce low frequencies.

Any particular speaker also has a limit to how much sound it can produce. The speaker cone can only move so far and so fast, and the speaker coil can only tolerate so much current. If you put too much current through the speaker coil, the coil and cone will move to the limit of their motion and stop. Like a spring that's stretched too far, the cone can't travel any further. When it reaches this point, the speaker cone no longer follows the audio signal accurately and the sound becomes distorted. If the current through the coil increases further, the coil will become very hot and may burn up. It will behave just like an incandescent light bulb.

The current passing through the telephone also passes through the telephone's speaker coil. As the current through the telephone fluctuates up and down, so does the current through the speaker coil and the speaker creates sound. Since talking into the microphone of any telephone causes the current in each telephone to fluctuate, it also causes the speaker in each telephone to create sound.

In principle, talking into your own telephone microphone should cause the speaker of your telephone to reproduce your voice, too. However, this effect is undesirable because it would affect your speech. If you were to hear the full audio signal from your voice through your own speaker, you would think you were talking too loudly and you would unconsciously start to talk more softly.

The sound you hear in your telephone speaker when you talk into your telephone microphone is called **sidetone**. Each telephone contains a balancing network that reduces sidetone. This network is usually a simple collection of electronic components that detects audio signals created by the telephone's microphone and keeps them from causing current changes in the telephone's speaker. The balancing network reduces the extent to which audio signals from your microphone affect your speaker so that you aren't fooled into talking too quietly.

| **CHECK YOUR UNDERSTANDING #3: Current Comes and Goes** |
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| Why are there two wires connecting your sound system to each of its speaker cabinets? |

## The Bell

When you aren't using your telephone, you usually hang it up. This action electrically disconnects the microphone and the speaker from the two telephone wires. But it also connects one other component of the telephone to the wires: the bell or its equivalent. The bell is a device that responds to an alternating current sent through the two telephone wires by the telephone company when a call is coming in. While the voltages present on the telephone wires during a conversation are small and safe, the voltages used to drive current through the bell are large enough to give you a mild shock if you touch both wires while the bell is ringing.

A real telephone bell uses this alternating current to energize an electromagnet (Fig. 10.3.7). One end of the electromagnet becomes a north pole and the other a south pole. Each time the current reverses, so do the poles of the electromagnet.

Situated between the two poles is an iron clapper. The clapper is magnetized by a small permanent magnet attached to its base so that it's attracted toward north poles and repelled by south poles. The electromagnet attracts the

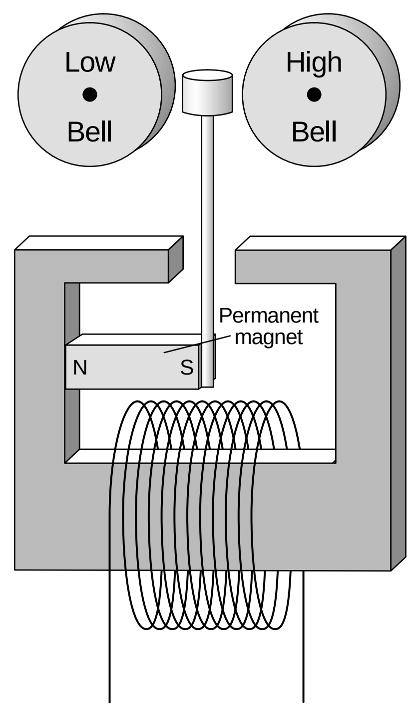

Fig. 10.3.7 - In the bell, an alternating current magnetizes an iron armature that pushes and pulls on the clapper of the bell.

clapper first toward one pole and then toward the other. The clapper swings back and forth between the poles as the current reverses and its end strikes two metal bells in the process. The bells ring. The two bells are usually tuned to an octave interval. That means that the high-pitched bell rings at twice the frequency of the low-pitched bell, giving the telephone its characteristic sound.

Most modern telephones have replaced the bell with electronic tones. They use the ring current to power a tone generating circuit and an amplifier, and produce the electronic sound with a speaker.

**CHECK YOUR UNDERSTANDING #4: People-Powered Telephones**

In movies, you occasionally see someone turning a hand-crank on an old-fashioned telephone. Turning that crank rings a bell in the operator's office. How does this work?

## Receiving and Making Calls

When the telephone rings and you pick up the receiver, you activate a switch that disconnects the bell from the two telephone wires and connects the speaker and microphone to those wires. The telephone's electric resistance suddenly decreases significantly. The telephone company detects the sudden decrease in electric resistance and it determines that you have received the telephone call. It stops sending the ring current, electrically connects the wires of the calling and receiving telephones, and begins to provide the steady current the telephones need in order for you to begin communicating. It also begins charging for the connection if someone is paying by the minute.

When you are done with the call, you hang up the telephone. The telephone company detects the sudden increase in electric resistance and it notes that you have hung up. It stops providing the steady current and stops charging you for the connection. If more than one telephone was active in your home, the telephone company doesn't see the rise in resistance until all of the telephones have been hung up. That's why even a single telephone that is "off the hook" will prevent all the telephones from working properly.

There are presently two forms of dialing: rotary and touch-tone. Rotary dialing has been almost completely replaced by touch-tone but the phone company still recognizes rotary dialing. When you make a telephone call using an old-fashioned rotary dial telephone, a complicated switch with a built-in mechanical timer goes to work. This switch briefly hangs up the telephone several times. When you turn the dial, you are winding the timer. When you let go, the timer unwinds and briefly hangs up the telephone several times in rapid succession. When you dial the number 5, the timer hangs up the telephone 5 times. The telephone company detects these brief hang-ups and uses them to control the automatic switching equipment that arranges the call. In fact, a person with a quick and steady hand can dial a rotary telephone by tapping the switch that hangs up the receiver. If you tap that switch five times, each separated by about a quarter of a second, you will dial the number 5.

Touch-tone telephones signal the telephone company by placing pairs of electronic tones on the telephone line instead of voice sounds. Actually, the wires don't carry the tones as sound—they carry the two tones as two alternating currents. When you press the 5 button on a touch-tone phone, two electronic devices in the telephone are activated and each produces a tone. The current flowing through the two telephone wires fluctuates with these two tones. The electronic devices that create these tones derive their power from the current through the two telephone wires, as do any other electronic devices in the telephone.

There are four different tones for the four horizontal rows of buttons and three more tones for the three vertical columns. When you press the 5 button, you get both the tone for the second row and the tone for the middle column. If you press two buttons in the same row or column, some older telephones will produce only the tone for that row or column.

The telephone company detects the tones with electronic devices that respond resonantly to those particular tones. The telephone company has seven tone-sensing devices, each looking for a particular frequency to appear in the current flowing through the telephone wires. When pairs of tones are detected, a computer determines which number button was pressed and uses that information to connect the call. Requiring that two specific tones be present to dial each number ensures that a person talking or singing while dialing doesn't accidentally dial a number with his or her voice.

**CHECK YOUR UNDERSTANDING #5: No Phone, No Connection**

If you accidentally unplug your telephone from the wall during a conversation, it hangs up. Why?