M. Analog Electronics I

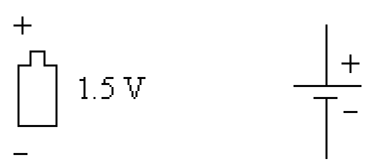
M-1. Flashlight

Our first circuit application is the flashlight. It is a simple electrical circuit with a battery, bulb, and wire or metal to connect the two. These components are discussed below. The first component we consider is the *battery*, the device that produces moving charge, i.e., electricity.

A battery gets charges moving for us. The battery separates charges chemically. Then the electric force serves as the force that makes the electrons move toward the positive region. A battery is sketched below in Fig. M-1 along with the symbol used by engineers for one battery cell. The minus is at the bottom, while the absence of electrons causes a plus region at the other terminal. If a wire were to connect both terminals (dangerous), electron flow through the wire to the plus terminal would dangerously exceed normal levels. This would be very bad for the battery for the flow would be too intense. The electricity must do some work, e.g., heat a bulb filament, so that the flow be within operating limits of the battery. Such a lower flow rate gives the battery time to keep up with the flow by constantly bringing the electrons internally back to the minus terminal. However, after the lifetime of the battery, the battery can no longer separate the electrons. We then say that the battery is dead.

A measure of the strength of the battery is given in *volts*. A typical flashlight battery has 1.5 V (1.5 volts); transistor radio batteries are 9-V batteries. If we stack batteries as in a flashlight cylinder, the voltages add. Two 1.5-V batteries in a flashlight result in a voltage of 3.0 V.

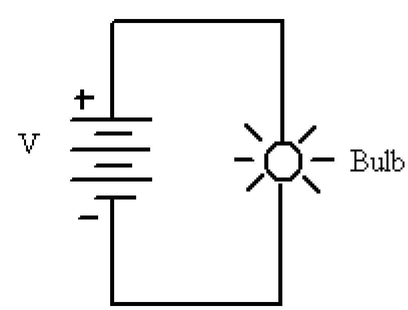
Fig. M-1. Battery and Symbol.



The simple circuit for the flashlight is given in Circuit 1. Suppose we have a bulb that will light up when 4.5 V is applied to it. We then stack three 1.5-V batteries in order to obtain 4.5 V. See the flashlight circuit for this bulb in Circuit 1 at the right.

The bulb consists of a fine tungsten filament surrounded by some inert gas (non-reactive). The filament heats up due to the current going through it. The lack of oxygen in the bulb prevents the bulb from burning up. The filament glows, giving off visible light and infrared light (heat).

Circuit 1. Flashlight.



Current is a measure of how many electrons pass a given point in one second. We need not concern ourselves with how many electrons move by per second. We simply use the convenient unit *ampère* or *amp*, abbreviated A. The letter I is used to designate current, e.g., I = 5 A (5 amps) .

1. *Direct Current* (DC). The current flows in one direction. The battery used in Circuit 1 supplies direct current in the circuit. A typical bulb in Circuit 1 may draw a current of 0.1 A (one tenth of an amp). It is convenient to use a smaller unit of current, thousandths of an amp or milliamps. The abbreviation for milliamp is mA. Since 0.1 A can also be written as 0.100 A, we readily see that we have 100 thousandths of an amp, i.e., 100 mA.

2. *Alternating Current* (AC). The current flows back and forth. This type of current is easy to generate by power companies. Our light bulb doesn't care which way the current flows. It would still light up if we used alternating current. Think of alternating current like a sine wave describing electrons pumping back and forth in a wire.

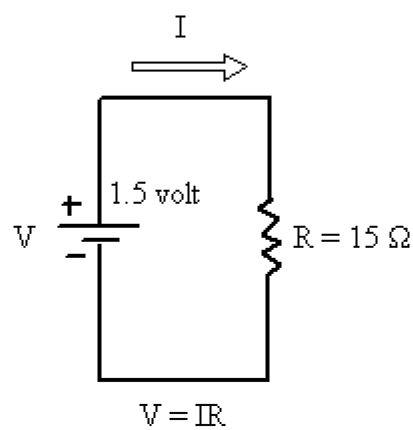
Resistance limits the flow of current in a circuit. Resistance is measured in *ohms*. The symbol for ohms is Ω. A *resistor* is a circuit element whose purpose is to provide resistance. Think of a resistor as a "clogged pipe with rags," where the "current of water" has trouble getting through. Before we see a dimmer circuit that will illustrate the importance of resistors, let's consider a simple circuit of a battery and resistor. This circuit is not useful for anything other than illustrating a basic principle of electronics: *Ohm's Law*.

Note that in Fig. M-2 below the current direction is pointed away from the plus side of the battery. This is a convention. The electrons actually move the other way. But since electrons are negative, we point the arrow in the opposite direction. This helps make the math simpler for engineers.

Ohm's Law relates the three quantities V, I, and R. The law states that V = IR. Think about this. You would expect it. If you keep the battery strength V constant, then less resistance (R) means more current (I) and vice versa. Recall that this logic is the same we used to discuss $v = \lambda f$, where the wave speed is constant. If you decrease λ, you increase f and vice versa.

Here is an example. For one cell, V = 1.5 volts. Consider a resistance of 15 Ω. Then, V = IR becomes 1.5 volts = I x (15 Ω). The current "I" must be one tenth, i.e., 0.1, A since one tenth of 15 is 1.5. We can also rearrange V = IR as follows: I = V/R = 1.5/15 = 0.1 A = 100 mA.

Fig. M-2. Current.

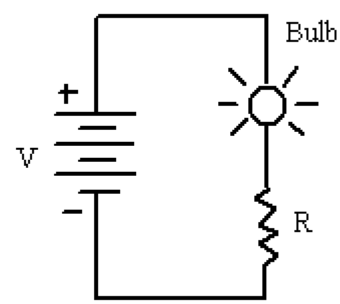


I = V/R = 1.5/15 = 0.1 A

M-2. Dimmer

The circuit at the right (Circuit 2) makes the bulb glow dimmer due to the resistor R. Can you design a three-way dimmer circuit so that the light bulb has three settings? HINT: Modify the circuit so the pathway at the bottom has three possible upward turns, one with resistor R_1 (this can be the resistor with the large resistance that will cause the bulb to glow very dim), a second with resistor R_2 (this can be a resistor with less resistance), and a third upward path that is a "pure" wire (no resistance). Then use the switch symbol seen in C3. Have your switch come down from the bottom of the bulb, allowing it to choose one of the three pathways to complete the circuit.

Circuit 2. Dimmer.



M-3. Flash

Circuit 3 (C3) introduces a new circuit element called a *capacitor* (C). The capacitor can be thought of as consisting of two metal plates. The battery symbol shows two cells. This is the standard number of cells to show (in a circuit diagram) with any written value by the side of the symbol.

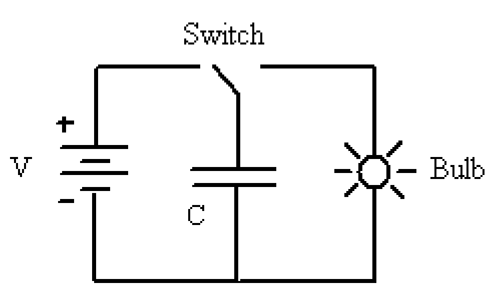
Note the switch symbol at the top. The switch can be thrown to the left or right. When the switch is thrown to the left, the capacitor is connected to the battery. Minus charges gather temporarily (–) on the bottom plate and the absence of electrons on the top plate makes the top plate positive (+).

The switch is then thrown to the right. Negative charges rush through the bulb to get to the other side (plus side) of the capacitor. Current flows through the bulb. However, since the capacitor loses its charge as electrons return to the top plate, the bulb is on for only an instant. The unit for capacitance is the *farad* (F), named after Faraday.

The capacitor is not a battery; it cannot remove electrons from the top plate and bring them back down to the bottom plate internally as a battery does. The capacitor only stores electricity and when this electricity is used up, the capacitor is neutral again (no net charge on either plate).

The rush of current is sudden and dies down quickly. If a resistor were in the charging left loop between the battery and the capacitor, the charging of the capacitor would take time since current flow would then be reduced to more of a trickle of flow due to the resistor.

C3. Flash.

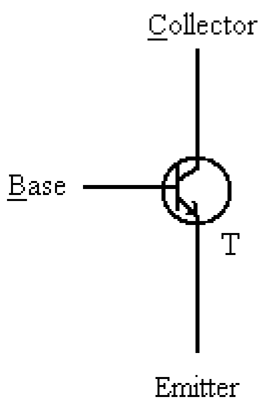


The circuit diagram depicts the standard use of two voltage cells to represent any voltage.

M-4. Delayed Light

A *transistor* is a circuit element with three wires protruding from a small container. The schematic of a transistor is seen in Fig. M-3. The three wires of the transistor are called the *base* (B), *collector* (C), and *emitter* (E). When a small amount of current enters the base (B) of the transistor, lots of current can then flow from the collector (C) to the emitter (E), provided that a battery is around nearby to supply the current. The small amount of current from B and the great amount of from C both leave the emitter E. We will not delve into the inner structure of a transistor.

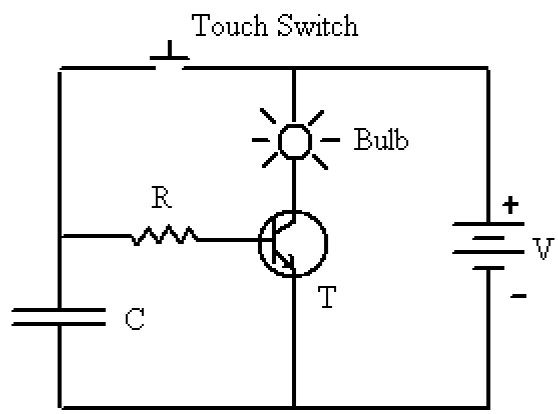
Fig. M-3. Transistor.



By carefully controlling the small base current, we can control the large currents capable of flowing from the collector to the emitter. Circuit 4 is a circuit that gives off light when the touch switch is pressed. When the touch switch springs back after release, the light stays on for awhile. After a certain time, the light then goes out automatically. Such a circuit is convenient for lighting a garage until you can drive the car out. After you're a block away or so, the garage light turns off by itself. However, Circuit 4 is a "doll-house" version of the real circuit.

When the switch is pressed, current rushes to the capacitor (C). The capacitor charges immediately since the path to it is clear. After the capacitor is charged, current trickles through the resistor activating the transistor. Current can now flow through the transistor, and the bulb glows. When the switch is released, it takes awhile for the charge on the capacitor to empty through the resistor. So the bulb stays on until the capacitor gives up its charge (discharges). After this, the capacitor is neutral, there is no current, and the bulb is off.

Circuit 4. Delayed Light.



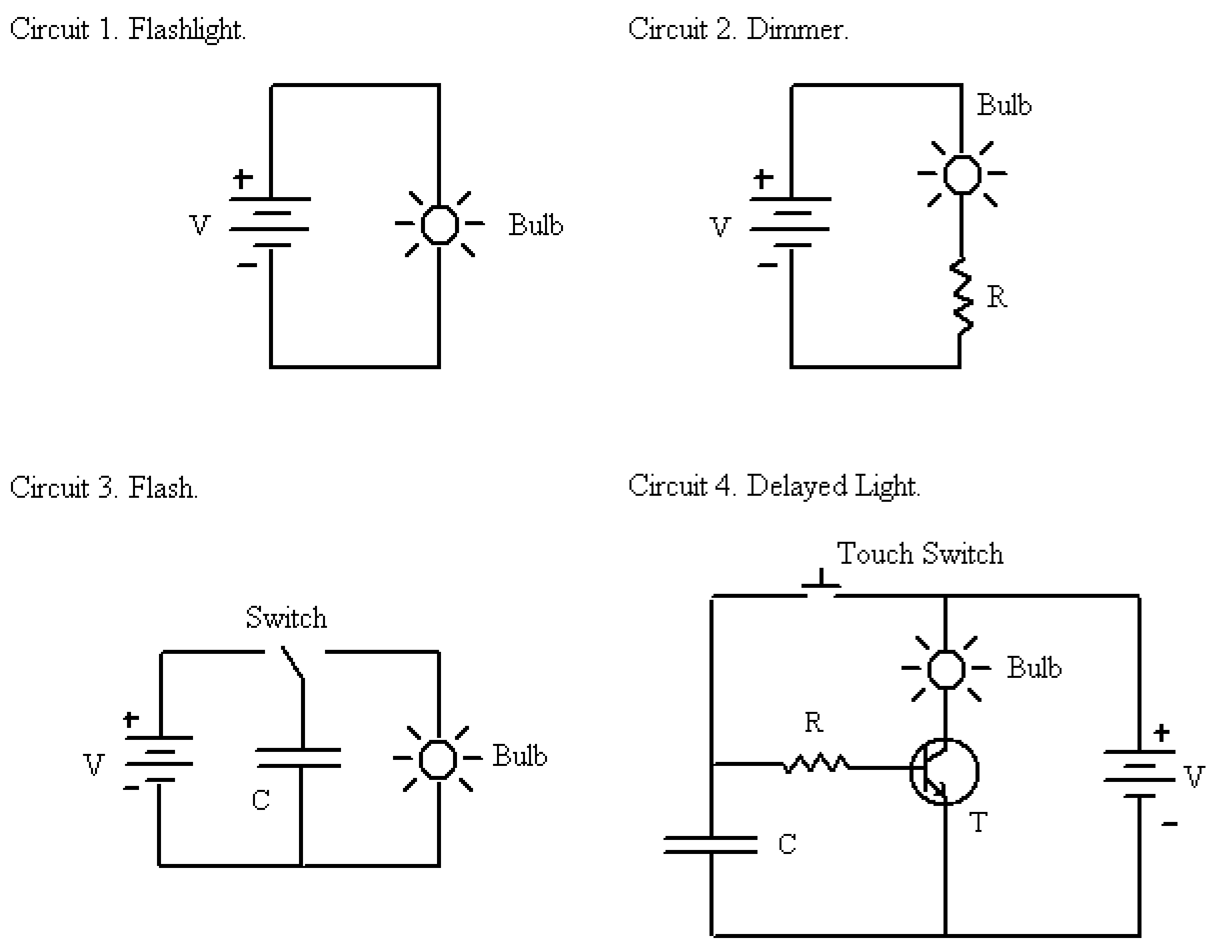
We will see later how a transistor can be used as an amplifier in a sound system. Can you modify the above circuit so that one needs to hold the switch down for awhile in order for the capacitor to charge fully? HINT: Insert a resistor in the vertical section of the upper left loop. Now it takes time to charge the capacitor. The light does not go on immediately. However, when the switch is released, the light will stay on for a while as before.

Let's review the four basic circuits we have encountered. These are reproduced in Fig. M-4 below. The simplest possible circuit is the flashlight. It consists of the minimum number of circuit elements in order to make a single circuit loop. You need a battery and one other element, in this case the bulb. There are only a few basic circuit elements engineers use as building blocks for circuit design, just as there are few notes in a musical scale.

Notes serve as building blocks for musical lines. For example, the common jazz blues-scale has only 6 notes, 3 of which lie outside the major scale we encountered earlier. The jazz improviser uses these notes in a traditional blues, perhaps only occasionally using other notes. Similarly, electrical engineers rely mostly on about 6 circuit elements: the battery (or power source), bulb (or some visual-display element), resistor, capacitor, transistor, and diode (which we haven't looked at yet). Observe how carefully each circuit below adds one more of the basic circuit elements.

The dimmer should have a variable resistor to vary the light intensity. Sketch an upward slanted (to the right) arrow across the resistor in the second circuit below. This indicates a variable resistor. Variable resistors have a turning knob to vary resistance.

Fig. M-4. Review of Four Basic Circuits.



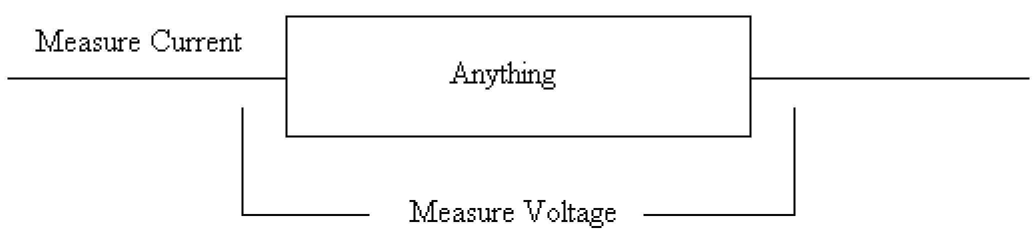
The source of energy for circuits is the battery or the electrical outlet on your wall. Batteries supply direct current (DC) while your wall outlet provides for alternating current (AC). The voltage of typical batteries is 1.5 V for the cylindrical variety and 9 V for the transistor batteries. The voltage from your wall outlet is about 120 V (110 or 115 V), alternating as a sine wave. Voltage for alternating current is defined as 70% of the amplitude.

Two aspects of electrical usage are important for cost analysis. These are the voltage you need and how much current you want to draw. If you need 3 V instead of 1.5 V, you need to buy 2 batteries and place one on top of the other. More voltage means more money. Also, if you tax the batteries, demanding lots of current, the batteries do not last as long. It costs to replace them. Engineers design bigger batteries with the same voltage so that more current can be supplied, but these bigger batteries are more expensive. Battery sizes for 1.5 volts include the common sizes AA, C, and D. You might need 8 size C batteries to get 12 volts (8 times 1.5 V) for a boom box.

To assess the cost, we need to know the voltage and the current. A simple index is obtained by multiplying these together. The result is called the *power* (see Fig. M-5 below). The unit for power is the watt, named after the famous Scottish inventor James Watt, who improved the steam engine in 1769. Watt's steam engine gave us the new form of power that led to the industrial revolution. However, the study of electricity was in its infancy then. We had to wait over another century for common uses of electrical energy in factories and homes. The light bulb was not invented until 1880 by Thomas Edison. It is appropriate to define the unit for power as the watt.

The power equals the voltage times the current (P = VI). This applies to both DC and AC circuits. We will give two examples, one for each of these types of circuits.

Fig. M-5. Calculation of Power Consumption.



Power = Voltage x Current

$P = VI$

Fig. M-6 illustrates a toy flashlight circuit with one cell. The current is measured to be 0.1 A. To measure current you simply break the wire and stick a meter in the path. The current then flows through the meter. You can measure voltage by changing the setting on the meter (multimeter) and touching each end of the battery (black probe to negative side, red to positive). The power is then given by the product. The answer is 0.15 watts, or 0.15 W. What is this power in milliwatts (mW)?

Fig. M-6. Power Example (DC).

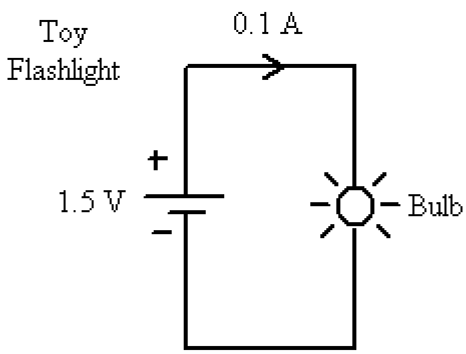
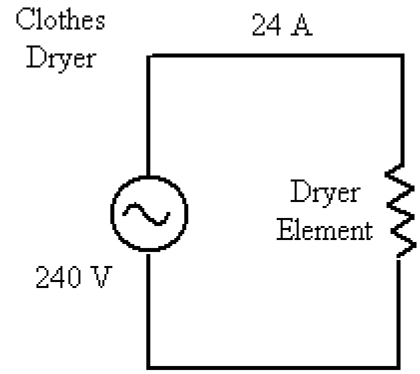


Fig. M-7 illustrates an alternating-circuit example. It is a clothes dryer. Note the circle with the wavy line inside. We use this symbol for an alternating voltage source. The wavy line is a sine wave. The voltage (about 120 volts) from your home outlet alternates as a sine wave at 60 Hz. Your clothes dryer is special, requiring two 120-volt outlets. The electrician wires up this combination, which takes a heavy-duty plug and wire to handle 240 volts. The dryer element is just a resistor that heats up. Note the large alternating current of 24 amps. The current oscillates at 60 Hz due to the alternating power source.

Fig. M-7. Power Example (AC).



$$P = (240 \text{ volts})(24 \text{ amps}) = 5760 \text{ watts}$$

The power consumption for the clothes dryer is 5760 watts, i.e., about 6000 W. This is a lot of power. The electrical company that supplies electricity to your home is interested in how long you keep this clothes dryer on. For example, suppose you dry your clothes for 2 hours. We say you use 12,000 watt-hours of electricity. We have multiplied again! The amount 12,000 watt-hours is more conveniently expressed as 12 kilowatt-hours (12 kWh).

Your electric company charges by the kilowatt-hour (kWh). Let's assume you are charged $0.10 for one kilowatt hour. Then, leaving your dryer on for 2 hours costs $1.20. This amount of money is what you pay for the energy used. The power gives you the level at which you use energy. It is a rate, analogous to speed. When you multiply speed by time, you get distance. Here, we multiply power by time to get the actual energy used.

Table M-1 below gives a list of common household electrical appliances and typical power consumptions. Usually there is a sticker on the device that lists the power. Sometimes voltage is listed (115 or 120) and the current instead of the wattage. You just multiply the given voltage value with the value for current in amps to get the power (wattage). The manuals for stereo and TV equipment also indicate the power consumption under the specifications section. Stereo "buffs" like specs. Unfortunately, due to the low level of science literacy in our culture, such information is often omitted in manuals for refrigerators, dishwashers, and other items. You have to look for the sticker on the appliance.

Due to those big values at the end of Table M-1 below for such household appliances as the electric hot water heater, the electric clothes dryer, and electric range/stove, the author switched to natural gas for his new home. Gas is available in the neighborhood. The electrical power for the gas water heater is 0 W. It is not plugged in. The same is almost true for the gas stove, but you need the lights, fan, and clock. During the 4-day blizzard/power outage in the early 1990s, many households were without heat, hot water, and a functional range/stove. With gas, the author enjoyed hot showers, hot spaghetti dinners, and heat - as the two gas fire-places cranked up living-room temperatures to 80°F!

Table M-1. Power Consumption for Appliances from the Author's Previous and Current Homes.

Electrical Appliance	Wattage	Electrical Appliance	Wattage
Night Light	4	Laser Printer	870
Record Turntable	5	Vacuum Cleaner	940
Yamaha Synthesizer	7	Coffee Maker	975
Tape Deck (no amp)	11	Dishwasher	1030
CD Player	14	Toaster	1050
VCR	27	Refrigerator	1150
Boom Box	38	Washing Machine	1180
Electric Typewriter	40	Oil Burner	1380
Notebook Computer	40	Hair Dryer	1400
TV (19" diagonal)	73	Popcorn Maker	1400
Stereo Receiver	130	Gas Furnace	< 1440
Desktop Computer	250	Hot Water Heater	< 4500
Blender	360	Clothes Dryer	< 6000
Garage-Door Opener	540	Central Air Cond.	< 6000
Microwave Oven	700	Range/Stove	< 12,000

Note the rather high power consumptions for devices that produce heat such as the coffee maker, toaster, popcorn maker, and portable hair dryer. The toaster is a simple circuit, essentially a power source connected to a resistor. The resistor gets warm as the current flows back and forth. The warmth heats and toasts the bread. The clothes dryer is basically the same idea, but doubling up on the voltage and using a motor to turn the drum that holds the clothes.

Central air conditioning is also high. Similar to the clothes dryer, it uses the doubled-voltage value of about 240 volts and draws much current. In comparison, electronic equipment such as tape decks, CD players, and VCRs have little power consumption. The TV or computer monitor demands more power, around 75 W, the same as a 75-watt light bulb. The power supply in a computer is typically 150 or 200 W to run the computer and peripherals. The power needed for the computer and monitor is around 250 W.

The author's portable computer (notebook) requires less, around 40 W. The night light uses the least power in the author's home. Calculate the monthly expense to keep the night light on, 10 hours per night for 30 days, if the cost per kilowatt-hour is a dime.

Electrical current is dangerous to the body. One must be very careful working with electrical appliances. Keep your hands dry. Water with its impurities conducts electricity very well. It acts like a wire. Never touch electrical components in circuits. Even if the circuit is off, capacitors can store much charge. It can still be dangerous. The third prong in an electrical wire connects the frame of the appliance to keep the outer surface neutral (at ground). If a wire or component becomes loose and touches the frame, current flows through the third prong and this should throw the circuit breaker, breaking the circuit at the source.

Once the author stuck his fingers into a wall outlet when he was 4 years old. He got shocked and cried for his dad. The wall outlet voltage is approximately 100 volts. The resistance for dry skin is in the range of 100,000 to 1,000,000 ohms (Ω). We will use 100,000 Ω. The current can be found from Ohm's Law: $V = IR$. We have $100 = I\,(100{,}000)$. The current $I = 100/100{,}000$. We cancel zeros to get $I = 1/1000$ A = 1 mA.

Now we check the health data to see if 1 mA is dangerous. A current of 1 mA is felt as a tingling sensation. However, if your skin is moist, the resistance is lower. For a resistance dropping by a factor of ten, the current goes up by the same factor. We then have 10 mA, beyond the 5-mA safe limit. You feel some shock. If you are 4 years old, this is quite an experience. Now if a baby sticks a finger in the mouth first, the resistance of the newly-wet skin goes way down and current soars upward.

At around 10-20 mA, sustained muscular contraction can prevent one from letting go if one grabs on to a live wire. This happened once to an electrician friend of the author. The electrician grabbed a live source with his hand. He couldn't let go. Luckily, he was standing on a ladder and jumped off using his legs. He fell, freeing his arm from the electrical source. Standing on a wet basement floor (electrical ground, neutral) and fooling with a power source can allow current to travel through the trunk of the body, through the heart.

Table M-2 below gives the physiological effects of various levels of current (60-Hz alternating like that coming from household outlets in the US) through the trunk of the body. The trunk is chosen so that the current passes through the heart. The heart is governed by natural biological forces electrical in nature. Introducing electrical current from outside can interfere with the normal beating of the heart. The dangerous currents are in the neighborhood of 100 to 300 mA. Note that for very high currents such as 6000 mA (i.e., 6 Amps) the heart freezes, then recovers. Remember though that the current is applied for only 1 second for the data in Table M-2.

The heart muscle gets confused when current is in the 100-300 mA range. It starts to beat irregularly. This effect is called *ventricular fibrillation*. It causes death. One can die within seconds or minutes. If an emergency team is nearby, the heart can be shocked again, this time sending in high current to freeze it. The hope is then to restart it beating normally.

The current path through the body is influenced by which part of the body touches the circuit and which other part of the body part acts as the ground. Current flows from higher voltage to lower voltage. The resistance of your skin/body plays a role. The usual amount of current drawn by the appliance you happen to stick your hand into is not the determinating factor. The important parameters are the voltage you touch and your resistance! You then use V = IR to calculate the current I.

Table M-2. Effects of Electrical Current on the Human Body.

Current (mA)	Effect after 60-Hz Alternating Current Goes Through Trunk of Body for One Second and then Stops.
1	Threshold of perception (tingling sensation).
5	Accepted as maximum harmless current.
10 - 20	"Let-go" current before sustained muscular contraction.
50	Pain. Possible fainting, exhaustion, mechanical injury.
100 - 300	Ventricular fibrillation (causes death).
6000	Heart freezes, then recovers.

Source: P. F. Leonard, "Characteristics of Electrical Hazards," *Anesthesia and Analgesia . . . Current Researches* 51, 797 (1972).

--- End of Chapter M ---

