Chapter 15

SEMI-CONDUCTING DEVICES

Say what you will about science's ability to mess up the planet's environment in general and life in particular, you have to be impressed with the way in which scientists have been able to use what is known about the make-up of the physical world to create useful devices. A spectacular example of this is the creation of semiconductors and their offspring, the diode and transistor. TVs, stereo systems, cars, computers--they are all based on semiconductors. This chapter looks at those materials and some of their derivative devices.

A.) Semi-conductors--"p-types" and "n-types":

1.) By themselves, silicon atoms (symbol *Si*--atomic number 14) bond in the same way as do all insulators--covalently. Each silicon atom has four valence electrons which are shared with four silicon neighbors (see Figure 15.1).

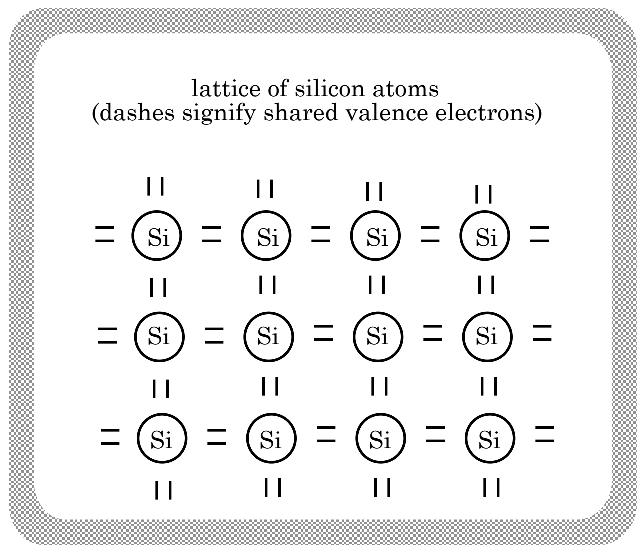


FIGURE 15.1

2.) A curious thing happens when a sprinkling of phosphorus atoms (symbol *P*--atomic number 15) is added to the pure silicon matrix. Phosphorus has *five* valence electrons.

a.) Each silicon atom around the phosphorus shares a single electron with its oddball neighbor (i.e., the *P*), leaving the phosphorus with one electron more than would have been the case if a silicon had occupied the spot (see Figure 15.2).

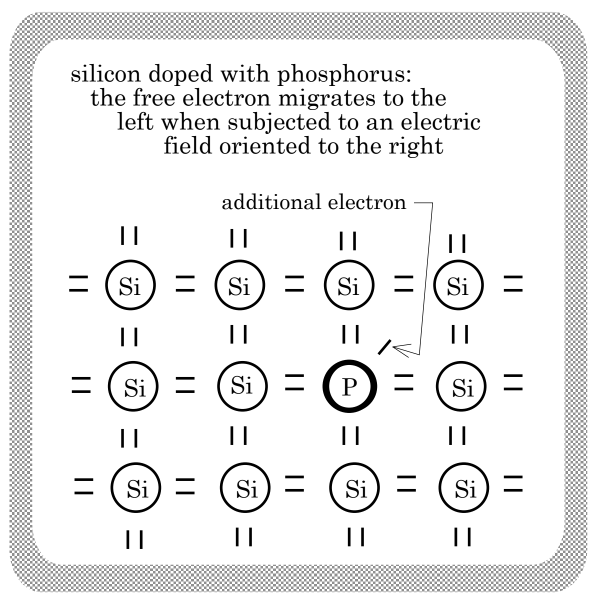


FIGURE15.2

Note: Placing impurities into an otherwise pure insulator is called "doping."

b.) Because phosphorus's valence shell holds only eight electrons, this extra electron doesn't fit into the *valence orbital* and has to occupy an energy orbital further out. In doing so, it is only loosely bound to the positive phosphorus nucleus.

c.) Due to this loose attraction, it takes nothing more than the energy associated with room temperature to break the extra electron away from its host atom. What's more, if put in an electric field, these free electrons will migrate through the structure creating an electron current (remember, conventional current assumes that positive charges are moving in the opposite direction--we'll stick to electron current for now). For a visual presentation of this, see Figure 15.3.

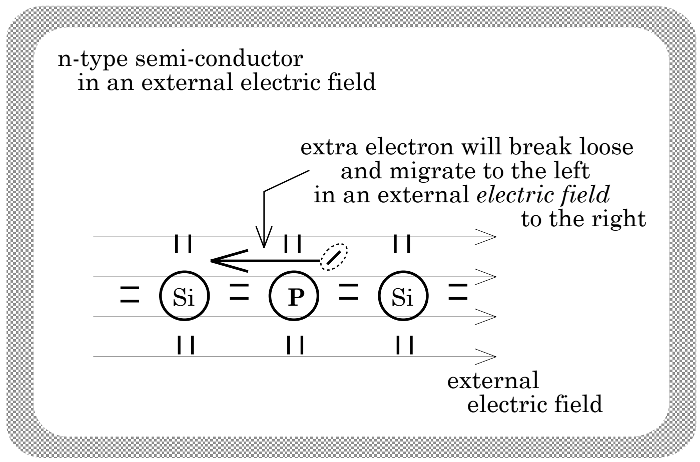


FIGURE 15.3

d.) Bottom line: If we take an *insulator* (silicon for example) and place the right impurities in it (phosphorus in this case), we will end up with an insulator that has *conductor-like* characteristics--a material through which *free charge* can migrate if an *electric field* is applied.

3.) A doped insulator like this is called a *semi-conductor*. In the case outlined above, negative charges (electrons) move through the material. As such, the material is called an *n-type* semi-conductor.

4.) A positive-charge version of the semi-conductor can be generated using boron (symbol *B*--atomic number 5) as the impurity. Boron has three valence electrons. Introducing it into a structure whose atomic composition is made up of silicon yields the following:

a.) Examine Figure 15.4. Each silicon atom around the boron wants to share a single electron

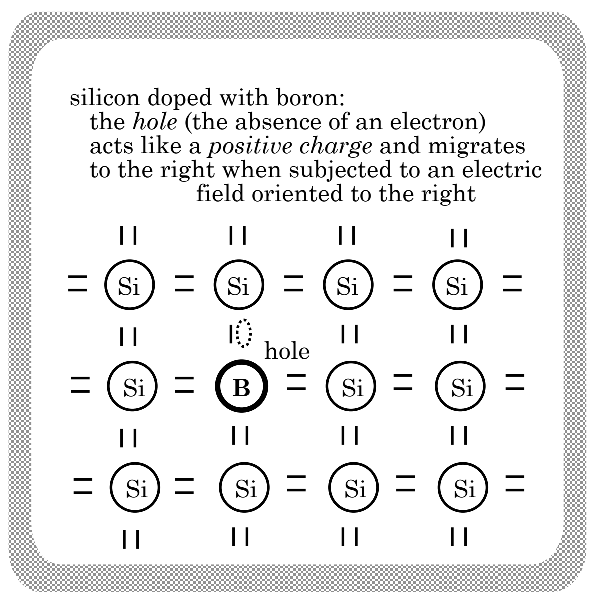


FIGURE 15.4

with its oddball neighbor (i.e., the *B*). After doing so, though, the boron still has one less electron than would have been the case if a silicon had occupied the spot.

In other words, there is a *hole* where an electron should be.

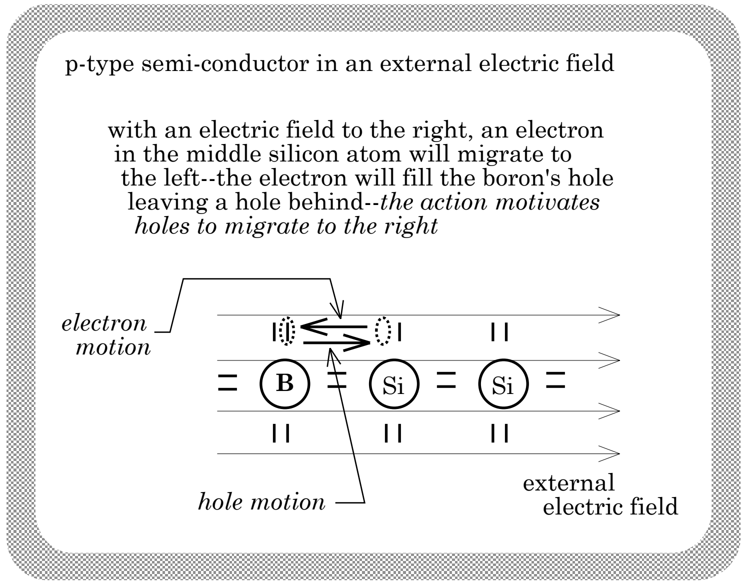


FIGURE 15.5

b.) A small electric field across this structure is all that is needed to motivate electrons from neighboring atoms to migrate into the vacancies (see Figure 15.5).

c.) When an electron leaves a silicon atom to fill a *hole*, it leaves a *hole* of its own behind. That new vacancy makes the area around that silicon less negative--hence, MORE POSITIVE--than it otherwise would have been (there is one less electron present).

Put another way, *holes* act like positive charges in the sense that where a *hole* exists, the area around it is more *positive* than it would otherwise have been.

d.) Bottom line: When an *electric field* is applied to this kind of semi-conductor, holes move through the structure. As such, the charge carriers are called *holes*, they are associated with positive charge, and the material is called a *p-type* semi-conductor.

B.) Diodes and DC Circuits:

1.) A diode is just a *p-type* and a *n-type* semi-conductor joined together. When placed in a DC circuit (see Figure 15.6), one of two things will occur:

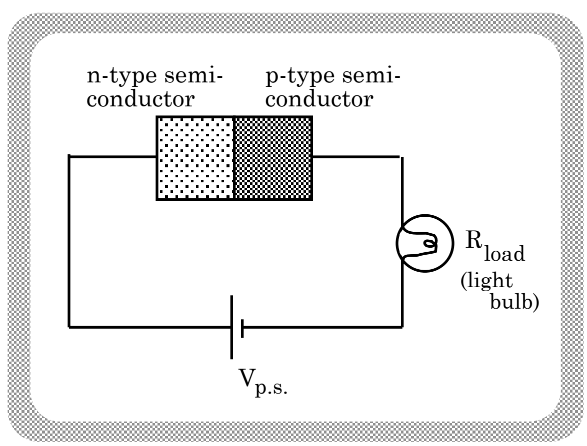


FIGURE 15.6

a.) If the power supply's polarity is as shown in Figure 15.7, the *holes* in the *p-type semi-conductor* will move to the right and *electrons* in the *n-type semi-conductor* will move to the left. This separation of charge carriers (holes going one way, electrons going the other) creates a *depletion zone* at the junction between the two materials (that junction is usually referred to as *a pn junction*).

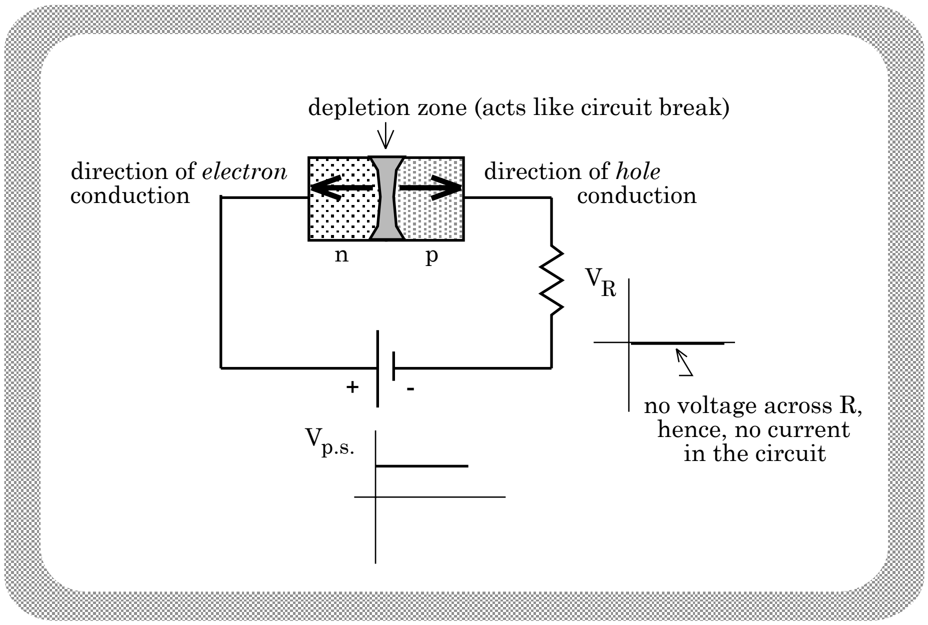


FIGURE 15.7

i.) This situation is called *reverse bias*.

ii.) With energy required to make the holes and electrons separate, a large *voltage drop* forms across the junction with essentially no voltage drop across the load resistor (i.e., light bulb).

iii.) As the voltage across the load resistor is proportional to the current through the resistor, no voltage across the resistor tells us there is *no current in the circuit* in this case. In other words, the light bulb will not light in this situation.

iv.) Put a little differently, when a *depletion zone* is formed, it acts like a *break in the circuit*. In that case, no current passes through the circuit.

b.) If the power supply's polarity is as shown in Figure 15.8, the *holes* in the *p-type semi-conductor* move to the left and the *electrons* in the *n-type* *semiconductor* move to the right. At the *pn junction* between the two semi-conductors, the *holes* and *electrons* combine and neutralize one another.

i.) This is called *forward bias*.

ii.) With relatively little energy required to make the holes and electrons come together (they are doing what they are inclined to do, anyway, with positive and negative charges being attracted to one another), there is very little voltage drop across the junction, almost all of the voltage drop occurs across the resistor, and as a consequence there is a large current in the circuit.

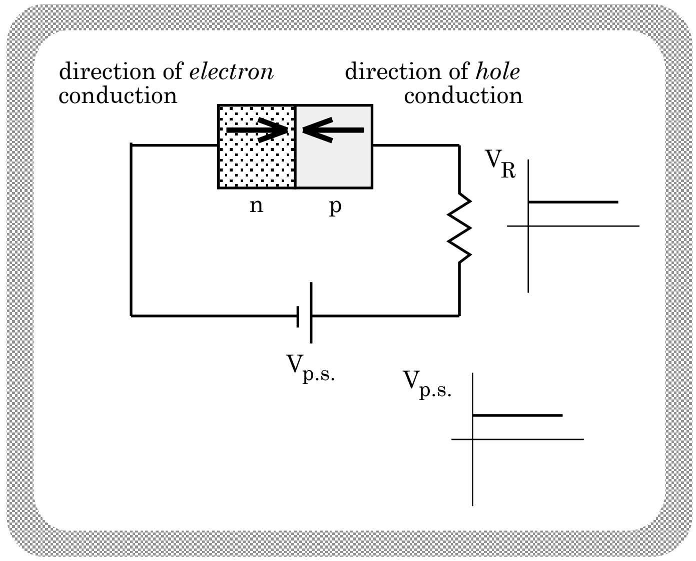


FIGURE 15.8

c.) Due to the way the holes and electrons in the semi-conducting material interact at a molecular level when in forward bias (i.e., when in conducting mode), the relationship between the voltage across a diode and the current through the diode is not completely straightforward. (In fact, it is an exponential with each .025 volt change increasing the current by a factor of *e*.)

Consider a silicon diode:

i.) For .1 volts across the diode, the diode appears *not* to be turned on. In fact, there will be a current, but it will be very small--maybe in the picoamps range (pico is 10^{-12}).

ii.) For .4 volts across the diode, the diode will still appear to be passing no current, In fact, there will again be a current--it will be larger than at the .1 volt level--but it will still be in the picoamps range.

iii.) Not until the diode voltage increases to between .5 volts and .6 volts will the current act as though there is nothing but a simple resistor in the circuit. When that happens, the current will jump all the way up into the milliamp range (milli is 10^{-3}).

iv.) The bottom line is that if we were to graph the voltage across the diode to the current through a diode in *forward bias*, we would get a section of low voltages that correspond to the appearance of *no current in the circuit*, then when the diode voltage hit approximately .6 volts the current would increase quite suddenly . A graph of this relationship is shown on the *right side* of the graph presented in Figure 15.9 (i.e., under the *forward bias* label).

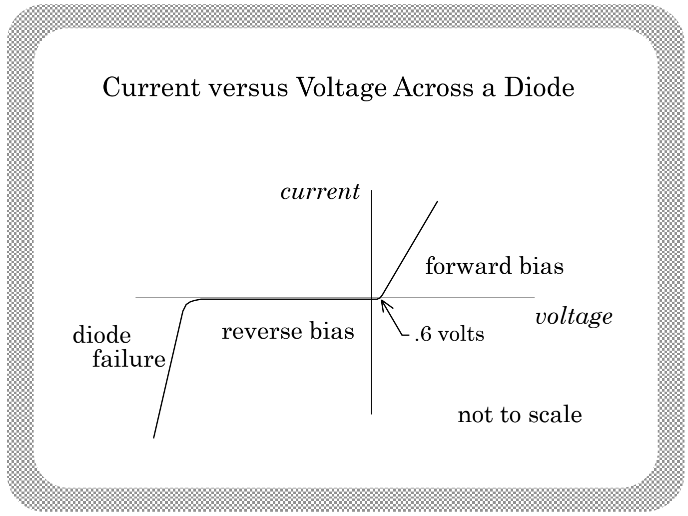


FIGURE 15.9

d.) You *can* get current to flow when the diode voltage is reversed.

i.) Although a reversed voltage, called *reverse bias*, does not generally allow current to flow in the circuit, a very, very large reverse voltage can set up an electric field that literally rips electrons out of the atomic structure of the diode and forces them to flow opposite the normal flow-through direction. This is called *breakdown*.

ii.) Breakdown occurs at a very specific, fixed voltage, for specific diodes.

Note: This "fixed voltage" characteristic of reverse biased diodes can be useful when you want . . . well, a fixed voltage in a circuit. The kind of diode that is designed to be used this way are called *Zenner diodes*.

e.) The left side of the graph shown in Figure 15.9 depicts the voltage/current characteristic of reverse bias in a silicon diode.

2.) The circuit-symbol for a diode is shown in Figure 15.10. The arrow points in the direction of conventional current flow during forward bias.

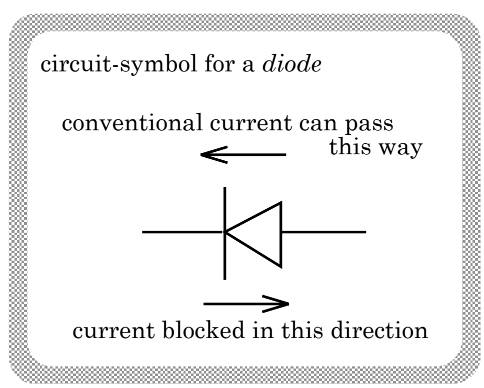


FIGURE 15.10

3.) Diodes physically look like resistors with one exception. They have a single band around their low voltage end instead of the four bands you find on resistors (see Figure 15.11). (The band is supposed to denote the vertical stop shown on the circuit symbol.)

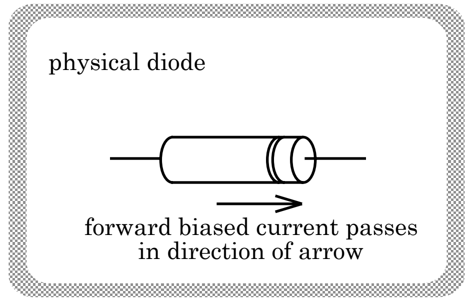


FIGURE 15.11

C.) Rectifiers:

1.) A rectifier is any electrical device that turns AC into DC.

2.) The simplest rectifier is a single diode. Used in this capacity, the diode is termed a *half-wave* rectifier. (Why it is called this will become evident shortly.)

3.) In an AC circuit, charge carriers jiggle back and forth as the alternating voltage that drives them switches polarity across the power supply. In a DC circuit, on the other hand, the current flows in one direction only. DC generated by a single diode placed in an AC circuit produces *lumpy* DC, but it is still DC--it is still current that flows in *one direction only*.

a.) The sketch in Figure 15.12 shows what a diode does in an AC circuit. (Note that V_R--voltage across a load resistor--is proportional to and directly reflects the current in the circuit.) Looking at the sketch, you can now see why a simple diode is called a *half-wave rectifier*.

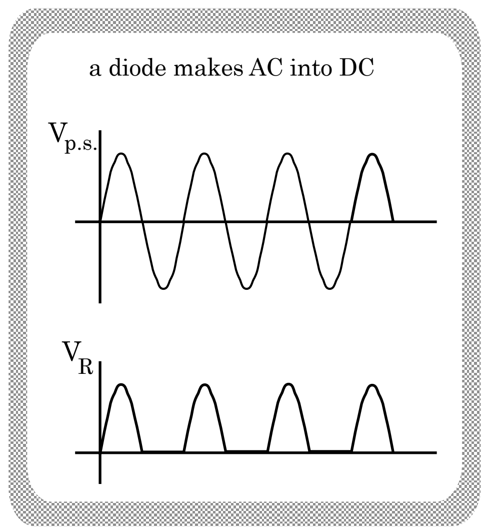


FIGURE 15.12

b.) DC generated by a single diode is inadequate for two reasons:

i.) First, current flows only during half of the power cycle (consequence--half the power available to the circuit is lost).

ii.) Second, the DC is lumpy.

4.) A more sophisticated rectifier is the *diode bridge*.

a.) Examine the *diode bridge* and *AC power supply* shown in Figure 15.13 (next page). With the voltage polarity such that the + *terminal* is on the upper side of the power source (this polarity is shown on the *inside* of the circuit diagram), the current in the circuit flows through the *load resistor* from left to right.

Note: By *load resistor*, we are talking about any device that requires electrical power. It could be a light bulb, a Skill saw, a toaster. Do not be thrown by the words *load resistor* in this context. It is simply a general term used to cover all possibilities.

b.) With the power supply polarity such that the + *terminal* is on the lower side of the power supply (this is shown on the outside of the circuit in Figure 15.13), the current in the circuit again flows through the *load resistor* from left to right.

c.) Bottom line: Current flows through the *diode bridge* in the same direction no matter what.

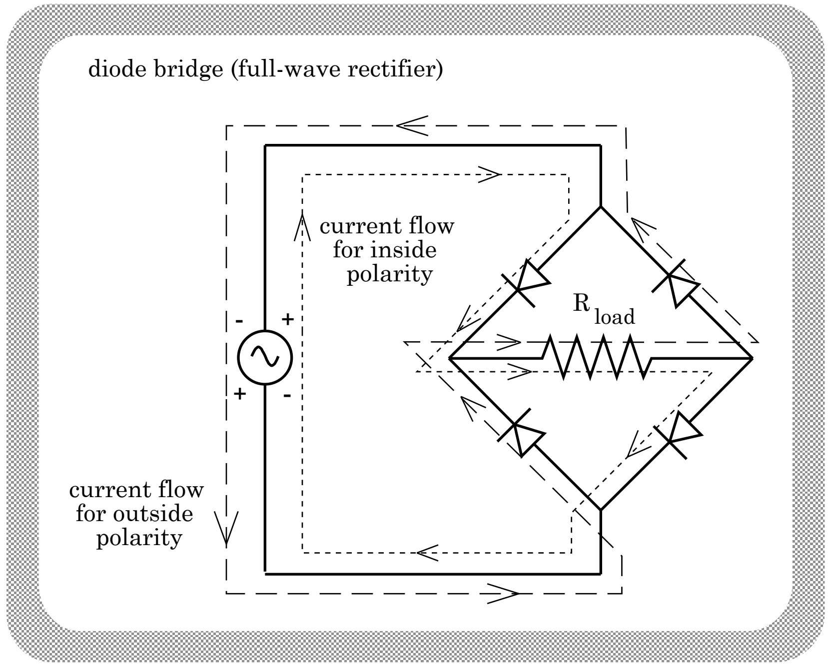


FIGURE 15.13

d.) A graphical representation of both the *voltage across the power supply as a function of time* and the *voltage across the load resistor as a function of time* is shown in Figure 15.14. Notice that the voltage across the resistor is still lumpy DC, but we are no longer losing half our power in the process.

The bridge flips half of the AC wave over (versus blotting half the wave out altogether). That is why a bridge is called a *full-wave rectifier*.

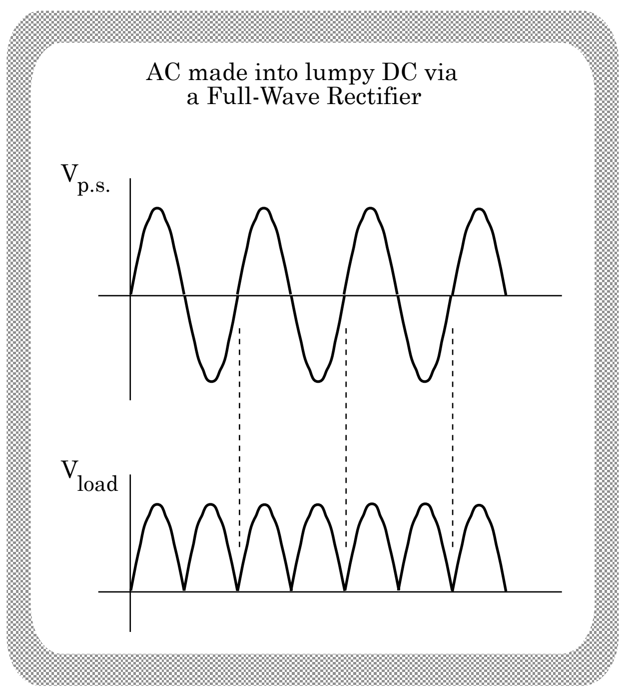


FIGURE 15.14

5.) About that lumpiness:

a.) To get rid of the lumpiness, a capacitor must be placed across the load resistor (see Figure 15.15).

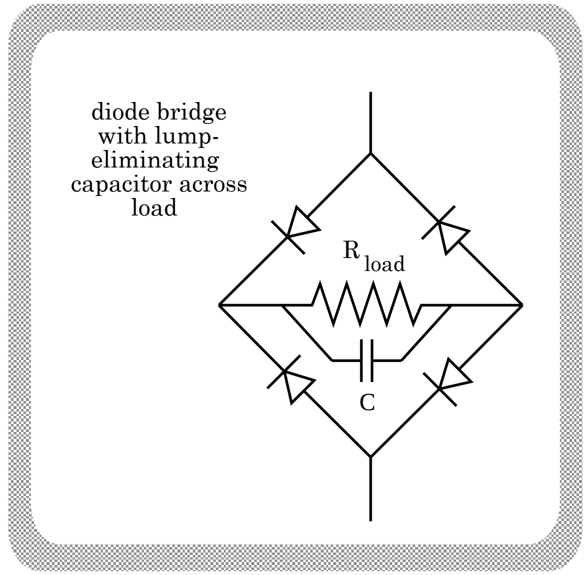


FIGURE 15.15

b.) With a capacitor in parallel to the resistor, the capacitor will charge up as current rises through the resistor. (Remember, the current through a resistor reflects the voltage across the resistor. Because the resistor and capacitor are in parallel, a rise in voltage across the resistor means a rise in voltage across the capacitor . . . exactly the condition needed to charge up the capacitor.)

i.) The voltage across the resistor and capacitor will sooner or later reach maximum and begin to decrease. As the circuit's voltage (i.e., the voltage provided by the power supply) begins to drop, the charged capacitor begins to *discharge* through the load resistor.

c.) With extra current flowing through the load resistor due to the discharging capacitor, the voltage across the load resistor stays higher than would normally be expected, dropping only slightly with time as the charge on the capacitor diminishes.

d.) After a time, the power cycle returns to higher voltages whereupon the voltage across the resistor increases. At that point, the capacitor also begins to re-charge and the cycle begins all over again. A graph of the superposition of all the voltages affecting the resistor is shown in Figure 15.16.

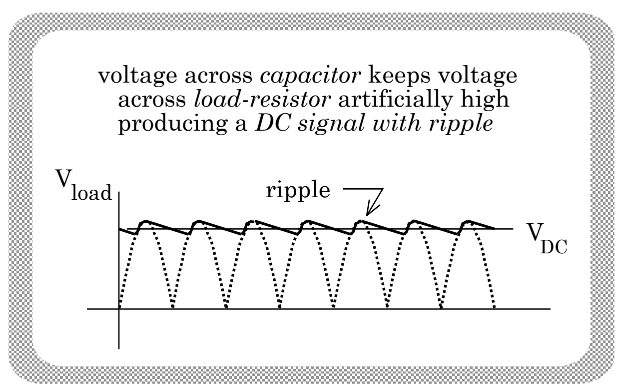


FIGURE 15.16

6.) The net *voltage across the load resistor* shown in Figure 15.16 is not completely constant. This variation in AC generated DC is called *ripple*.

a.) A good power supply will have less than 2% ripple with cheaper power supplies having ripple as large as 5%. In both cases, the variation is comparatively little--so small, in fact, that it is not normally evident even when viewed on an oscilloscope.

7.) Summary: A laboratory power supply generates DC by taking the 110 volt RMS voltage provided by the wall socket, using a transformer to step the voltage up or down depending upon the need, and passing the signal through a diode bridge (full-wave rectifier) coupled with a capacitor wired in parallel to the output terminal (i.e., the terminal into which the load is to be plugged). The output DC voltage will have some ripple, but it will be relatively lumpless.

Isn't this fun?

D.) Light Emitting Diodes (LEDs):

1.) When holes and electrons recombine at a diode's *pn junction* when the diode is in "forward bias" mode (i.e., when current is flowing so as to pass through the diode . . . versus being blocked by it), energy is given off.

a.) This energy shows itself in two ways. Diodes heat up and they give off light.

b.) For silicon diodes, the light given off is in the infrared range and, hence, is not visible to the naked eye.

2.) An LED, or *light emitting diode*, is a diode that is made up of semi-conducting materials that emit light in the visible range when current passes through it.

3.) The circuit symbol for an LED is shown in Figure 15.17. As usual, the arrow points in the direction of conventional current when the diode is forward biased.

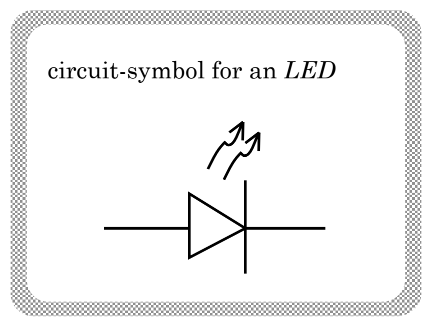


FIGURE 15.17

4.) LED's are physically dome-shaped and can be red, green, orange or yellow.

a.) Fresh from the factory, an LED has two leads of different lengths. The longer lead is the anode, or high voltage side; the shorter lead is the cathode, or low voltage side.

b.) Even if the lead lengths are not obvious, it is possible to tell which lead on a

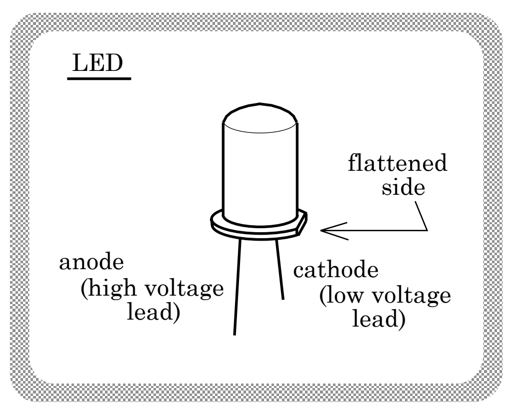


FIGURE 15.18

diode is which. The low voltage side of an LED is physically flattened (see Figure 15.18).

i.) This flattening is not always visually obvious, but it is evident to the touch. If you are not sure, run your finger around the side of the dome and the flattened area will stand out.

E.) *npn* Transistors:

1.) The semiconductor arrangement shown in Figure 15.19 is essentially two diodes back-to-back. Called an *npn transistor*, the arrangement as set up will not pass current in either direction in a normal DC setting.

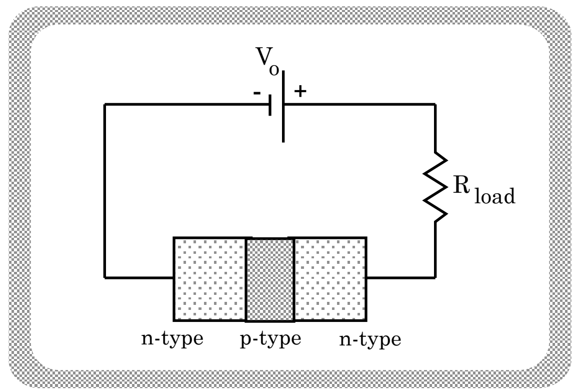


FIGURE 15.19

Note 1: A transistor is an extremely delicate device in which the central section of semi-conducting material is wafer thin (the side sections are not enormously thick, either). The sketch is radically out of scale so you can see how the insides of the device works.

Note 2: There are also transistors in which an *n-type* semiconductor is sandwiched between two *p-type* semiconductors. These are called *pnp transistors*. They will be discussed in the next section.

2.) Consider what the DC power supply in Figure 15.19 does to the various bits of semi-conducting materials making up the device.

a.) Given the power supply's polarity, the *electrons* in the *n-type* semi-conductors will move to the right and the positive *holes* in the *p-type* semiconductor will move to the left (see Figure 15.20).

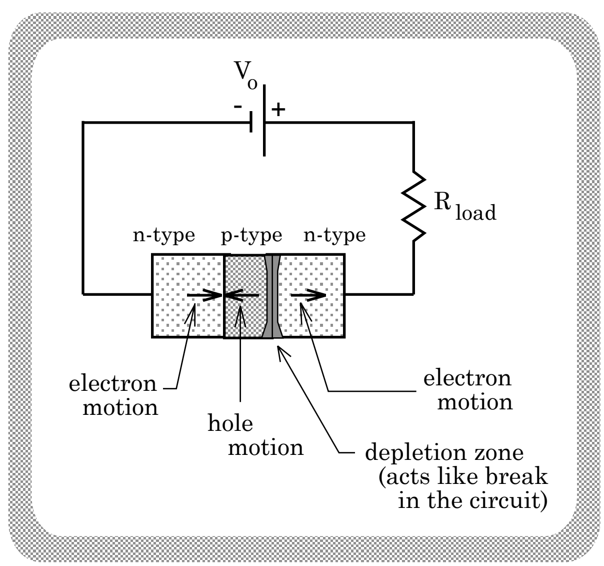


FIGURE 15.20

b.) What this means is that electrons and holes will combine across the left *pn* junction, but a *depletion zone* will be created along the right *pn junction*. (Note that if the power supply's polarity had been reversed, the depletion zone would have been set up along the left *pn junction*.)

c.) The depletion zone acts like a break in the circuit, stopping current from flowing altogether.

Note: Notice that the power supply in this circuit is trying to push current in a *clockwise* direction (see Figure 15.21).

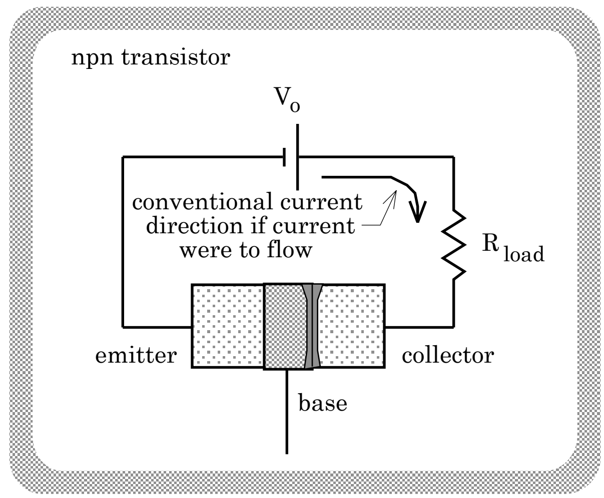


FIGURE 15.21

3.) Points of order: For an *npn transistor*:

a.) The semi-conducting piece into which conventional current would flow if it could flow is called the *collector* (see Figure 15.21)

b.) The semi-conducting piece out of which conventional current would flow if current could flow is called the *emitter*.

c.) The semi-conducting section that is sandwiched between the *collector* and *emitter* is called the *base*.

d.) This *collector/emitter* terminology makes the most sense in the context of an *npn transistor*. When conducting, the *collector* collects conventional current while the *emitter* emits conventional current.

Note: This is EXACTLY OPPOSITE the case for a *pnp transistor*. That is, when conventional current passes through the *emitter/collector* pathway of a *pnp transistor*, current ENTERS the *emitter* and LEAVES via the *collector*. (we will discuss this shortly.)

4.) What is interesting is that if we are clever, we can make current flow through the load resistor in the circuit shown in Figure 15.19. How so?

a) Let's assume we can make the *base* electrically positive relative to the *emitter* (we would do this by making the voltage at the base greater than the voltage at the emitter--how we might physically do this will be discussed later). What happens?

b.) As shown in Figure 15.22a, *holes* in the *p-type* semi-conductor just to the right of the base-connection will be repulsed by the positive base and will migrate to the right. Electrons in the right-side *n-type* semi-conductor near the base will be attracted to the positive base and will migrate toward the left. The holes and electrons will meet at the junction and the depletion zone will be compromised.

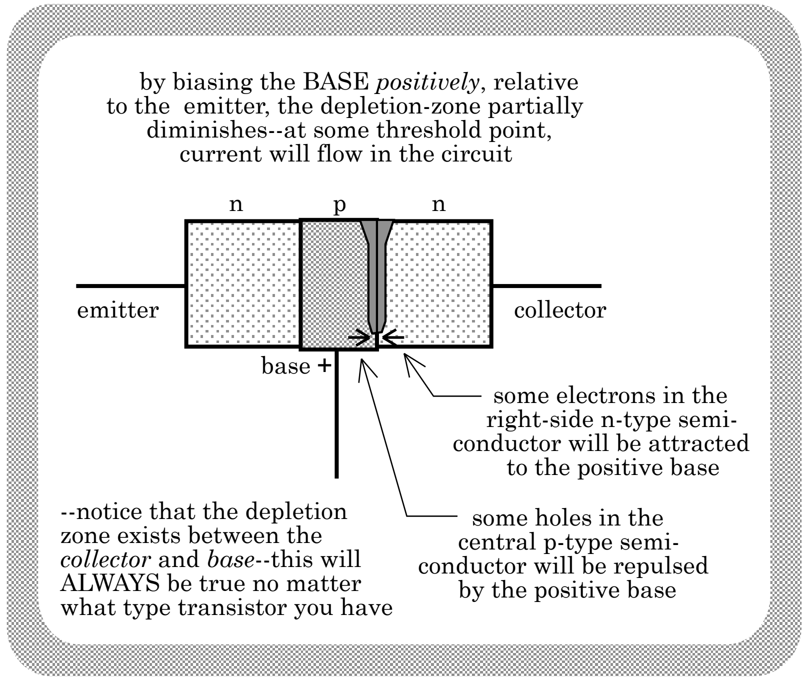


FIGURE 15.22a

c.) In the simple view:

i.) If the base is made just a little positive, relative to the emitter, the depletion zone will be diminished only slightly and only a small current will pass through the emitter/collector pathway.

ii.) If the base is made "more" positive, relative to the emitter, the depletion zone will diminish a lot and a significant current will flow through the emitter/collector pathway.

Note: It should be emphasized that the break due to the depletion zone is always at the *COLLECTOR/BASE junction*. You will never find a break at the *emitter/base* junction.

d.) That was the simple view. The *reality* of the situation is a little more complex.

i.) The first thing to know is that there is a linear relationship between the *base current* i_b (this is the current that passes into or out of the base), the *collector current* i_c and the *emitter current* i_e. Specifically, the collector current is ALWAYS equal to a constant times the base current, or $i_c = \beta i_b$ (see Figure 15.22b on the next page).

ii.) The constant *beta* is symbolized by a β and is referred to as the transistor's *gain*. (Again, look at Figure 15.22b for a summary.)

iii.) THIS IS IMPORTANT! We've talked about the voltage of the base, relative to the emitter, as what governs the size of the depletion zone. A more important consequence of the way transistors work is that the current *through the base* is linked linearly to the current *through the collector*.

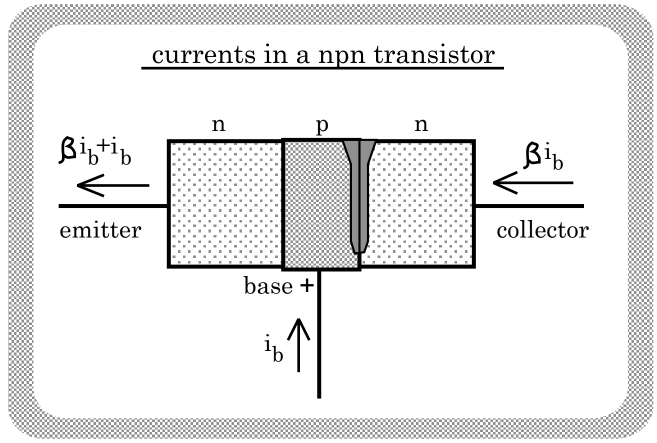


FIGURE 15.22b

iv.) It is not unusual for the *beta* of a transistor to be 100 or even 1000. Put a little differently, it is not unusual for the current through the collector to be 100 times the current through the base.

5.) Several points of order: The various ways you can symbolize an *npn* or *pnp* transistor in a circuit are shown in Figure 15.23.

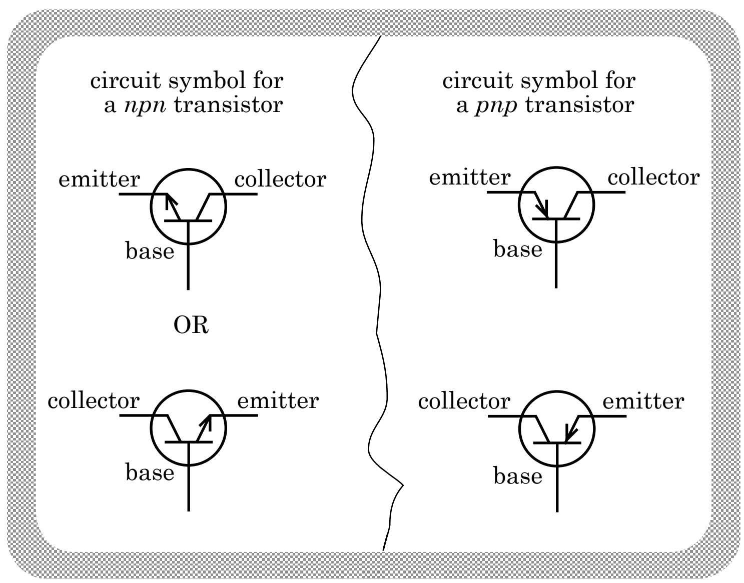


FIGURE 15.23

a.) Note that the only difference between the circuit symbol for a *pnp* transistor and a *npn* transistor is the direction of the arrow inside the circle. For *npn transistors*, the arrow points away from the base. For *pnp transistors*, the arrow points toward the base.

b.) Note that the arrow ALWAYS identifies the position of the transistor's *emitter* in the circuit.

c.) Note that in ALL CASES, the direction of the arrow designates the direction conventional current will flow through the transistor when, in fact, current does flow through the transistor. This is true for both the base/emitter current *and* the emitter/collector current.

6.) So how are transistors used? Figure 15.24a presents one way in which a *npn transistor* can be made to act like a *switch* in a circuit. Notice that I've included the base, collector and emitter currents for easy viewing.

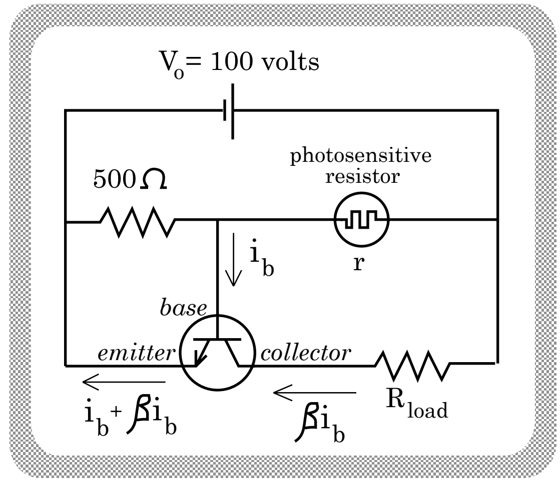


FIGURE 15.24a

Note 1: The odd looking, circled symbol in the circuit is that of a photosensitive resistor. The resistance of a photosensitive resistors varies depending upon the amount of light that impinges on its photosensitive surface. The more light on the surface, the less resistance the resistor animates.

Note 2: Don't get hung up on the math that follows. It is there to provide us with high-current data (remember, the base/emitter junction is really a diode--at *low current*, it has an exponential voltage/current characteristic) from which we can draw conclusions about how the *base voltage* and *base current* act when a transistor is being used as a switch.

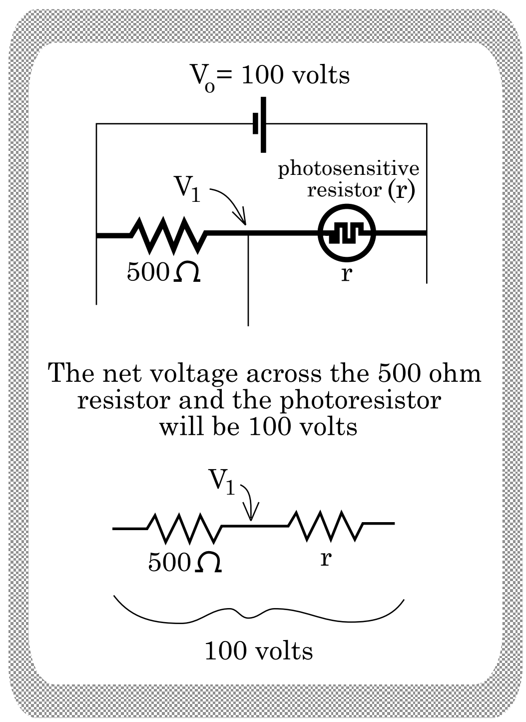


FIGURE 15.24b

a.) To start with, let's do a conventional analysis of the circuit in Figure 15.24a (we will be doing a lot of approximating here).

i.) Call the voltage at the base V_1 (Figure 15.24b shows this).

ii.) Look at Figure 15.24c. Note that as the emitter is connected to the battery's ground, its voltage is zero and the voltage across the base/emitter junction is just V_1. This will be important later.

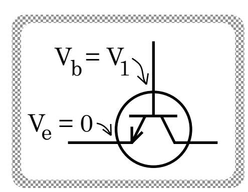


FIGURE 15.24c

iii.) Go back to Figure 15.24b. In our circuit, the voltage across the combined 500 Ω resistor and photoresistor is 100 volts. (This dual-resistor set-up is called a *voltage divider*. It is the basis of a rheostat).

If we take the fraction of voltage that resides across the 500 Ω resistor (that is $\frac{500}{500+r}$) and multiplying by the total voltage (100), we get the voltage across the 500 resistor. But as the left side of the 500 resistor is attached to ground and, hence, has zero voltage, the calculated voltage difference across the 500 Ω resistor will numerically equal the absolute voltage V_1 (aren't we clever?). That quantity is:

$$V_1 = \frac{5x10^4}{500+r}.$$

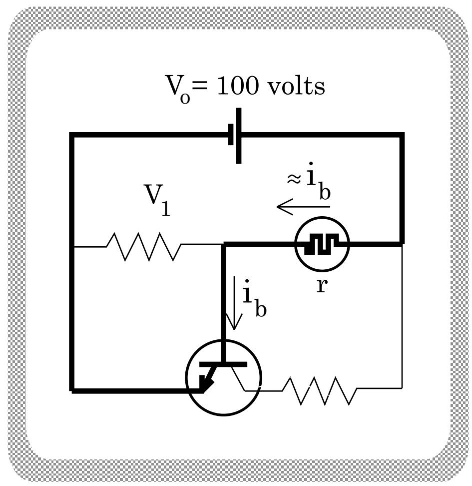


FIGURE 15.24d

iii.) Look at Figure 15.24d. The current coming into the V_1 node from the photoresistor will be considerably more likely to pass down through the tiny resistance of the transistor section than through the large 500 Ω resistor. As such, we can approximate the base current i_b to essentially be the same as the current through the photoresistor.

iv.) Using Kirchoff's Second Law on the darkened section of the circuit in Figure 15.24d, we find, to a good approximation, the base current i_b to be:

$$i_b = \frac{100 - V_1}{r}.$$

b.) Having done all of this math, let's assume the *gain* for the transistor is $\beta = 100$. Remembering that at very low voltage, the current acts exponentially across the base/emitter *pn* junction, let's do a little thought experiment.

i.) To start with, assume there is very little light on the photoresistor so that its resistance is, say, 1MΩ (1,000,000 Ω). We measure V_1 and i_b and record.

ii.) We change the light content thereby changing the resistance of the photoresistor. Again, we measure and record.

iii.) We do this over and over again until you have enough information to fill up the table shown to the right.

transistor as a switch

photo-resistance r	V_1	i_b	$i_c =$ i_b (ie., thru load)
1 M	.05 volts	∠ 1 pA	∠ 100 pA
500 K	0.1 volts	∠ 1 pA	∠ 100 pA
200 K	0.25 volts	∠ 1 u A	∠ 100 u A
100 K	0.5 volts	∠ 100 u A	∠ .01 A
50 K	0.6 volts	= 2 mA	= 0.2 A
25 K	0.6 volts	= 4 mA	= 0.4 A
10 K	0.6 volts	= 10 mA	= 1.0 A

Note 1: The math we developed earlier is usable once we get to the 100 KΩ range but not before due to the oddball exponential character of pn junctions.

Note 2: The term *pA* stands for "pico" amps, or 10^{-12} amps, μA stands for "micro" amps, or 10^{-6} amps, and *mA* stands for "milli" amps, or 10^{-3} amps.

7.) What have we gained from our little exercise? Knowing the base/emitter voltage V_1 and the collector/load current i_b for several situations, we can draw some conclusions about transistors as switches.

a.) Let's assume the load in our circuit is a small motor. Looking at the data in the table, we can see:

i.) For 1 MΩ of photoresistance, the base voltage V_1 is .05 volts and the base current i_b is minuscule (less than 10^{-12} amps). As such, the load sees a collector current βi_b that is also tiny (10^{-10} amps) and the motor does not run.

ii.) As the photoresistance moves from 1 MΩ to 200 kΩ, the base/emitter voltage V_1 rises to .25 volts and the base current increases from 10^{-12} amps to 10^{-6} amps. This still leaves the load with a collector current of only .0001 amps. This is not enough to drive the motor, so the motor remains *off*.

Note: The *base/emitter* junction is essentially a *pn* diode junction. As such, it should not be a surprise that the relationship between the base current and the base/emitter voltage (see Figure 15.25) looks like the graph of a forward biased diode (Figure 15.9). Conclusion, we shouldn't expect much in the way of current until we get in the vicinity of .6 volts.

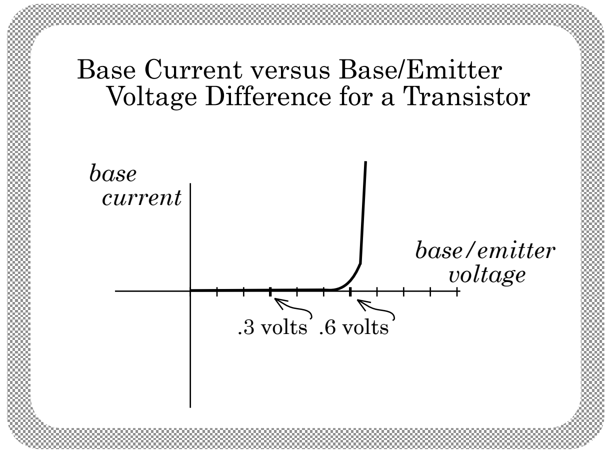


FIGURE 15.25

iii.) As the photoresistance moves from 200 kΩ to 100 kΩ, the base/emitter voltage rises to .5 volts and the load (collector) current approaches .01 amps. We haven't yet gotten to a current that will run the motor, but we are getting close.

iv.) At a photoresistance of 50 KΩ, the base/emitter voltage is around .6 volts and the load (collector) current reaches .2 amps. This is enough to turn the motor *on*.

Note: This .6 volts value for the voltage across the base/emitter junction is pretty much the largest that voltage will ever be (actually, it can get close to .7 volts, but people usually take the average "running" voltage for a silicon diodes and transistor to be .6 volts). This is due to the fact that there is not a depletion zone along the base/emitter junction, only a kind of charge inertia that has to be overcome before the transistor can maintain a substantial current. Once that threshold is met, charge flow keeps that voltage more or less constant.

v.) From here on, the load current changes inversely with the photoresistance. That is, when the photoresistance drops to 25 kΩ, the load current becomes .4 amps. When the photoresistance drops to 12.5 kΩ, the load current becomes .8 amps. When the photoresistance drops to 10 kΩ, the load current becomes 1.0 amps, etc.

d.) In short, there is clearly a light intensity that produces in the photoresistor a resistance that motivates the transistor's base current, hence its collector current (βi_b), from a state of *not* being able to drive the load motor to a state of *being* able to drive the load motor.

Put a little differently, our transistor, in conjunction with the photoresistor, has acted like a switch.

F.) *pnp* Transistors:

1.) The semiconductor arrangement shown in Figure 15.26 is that of a *pnp transistor*. As was the case with the *npn transistor*, there will be a depletion zone created along the device's collector/base junction and an appreciable base current will not flow unless the base is biased appropriately.

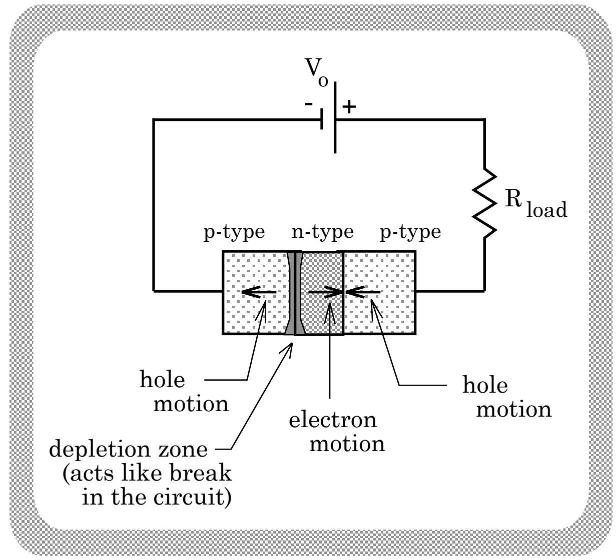


FIGURE 15.26

Note: Notice that if the base is biased *negatively* (see Figure 15.27), conventional current will flow clockwise in the circuit shown in Figure 15.26. (Again, the depletion zone is *always* at the *collector/base* junction.)

2.) Things to know:

a.) For a *pnp transistor,* the semi-conducting piece into which conventional current will flow, assuming current *can* flow, is called the *emitter*. (This is exactly opposite that of the *npn transistor*.)

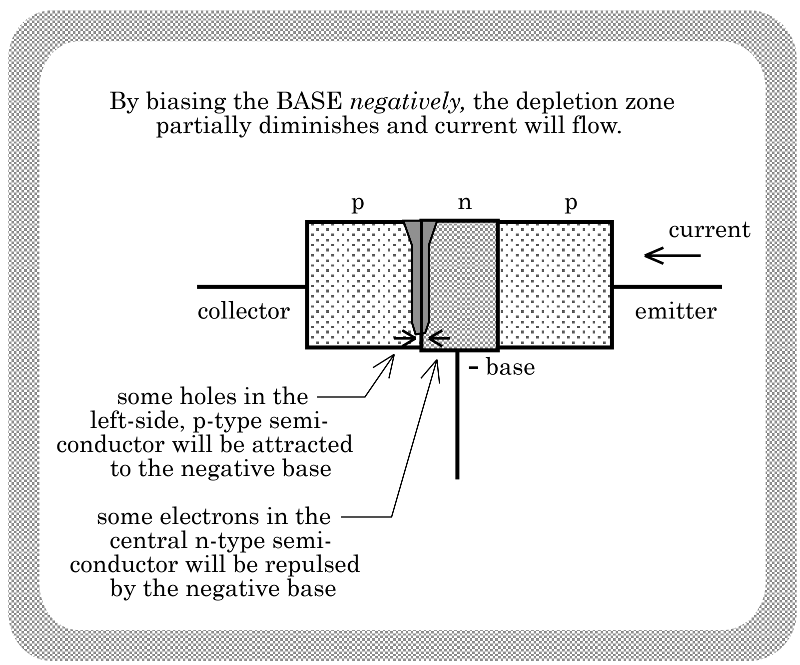


FIGURE 15.27

b.) For a *pnp transistor,* the semi-conducting piece out of which conventional current will flow is called the *collector.*

c.) For a *pnp transistor*, the semi-conducting section that is sandwiched between the collector and emitter is still called the *base*.

d.) You can do the same kinds of things with a *pnp transistor* as you can with a *npn transistor*. You simply have to remember that:

i.) The voltage of the base must be *less* than the voltage of the emitter (i.e., the base must be *negative*, relative to the emitter);

ii.) The base current i_b will flow *out of* the base;

iii.) And circuit current flows *into* the emitter and *out of* the collector.

e.) Just to remind you, I am reproducing Figure 15.23 so you can see the difference between the *npn* and *pnp* circuit symbols.

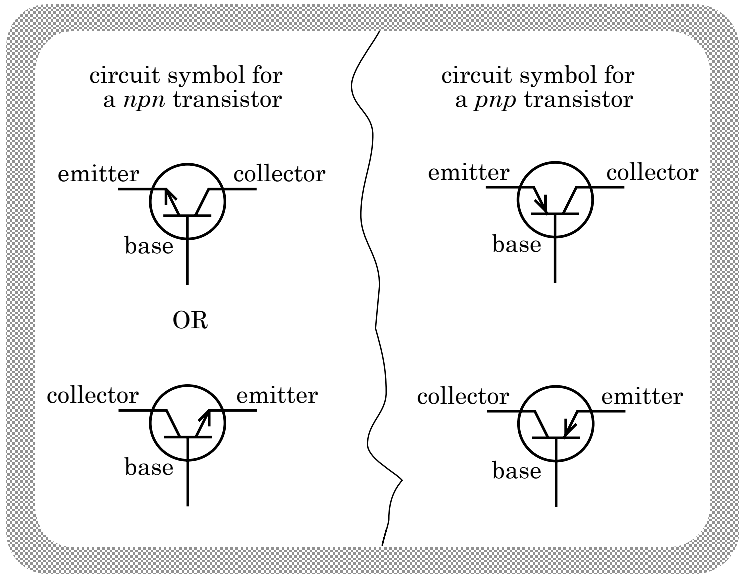


FIGURE 15.23

G.) Your Solar Robot:

1.) Now the fun. We would like to build a small, solar robot. To motivate the little guy, we need some way to charge up a capacitor to full capacity, then have it discharge through a motor.

This is not as trivial an exercise as it may seem. Nevertheless, a circuit that will do the job for us is shown in Figure 15.28. Your thrill, aside from building the device in lab, is to understand the ins-and-outs of how it works. The basics of the circuit are outlined below.

a.) Our goal is to have the charged capacitor discharge through the motor along the pathway outlined in Figure 15.29 (next page).

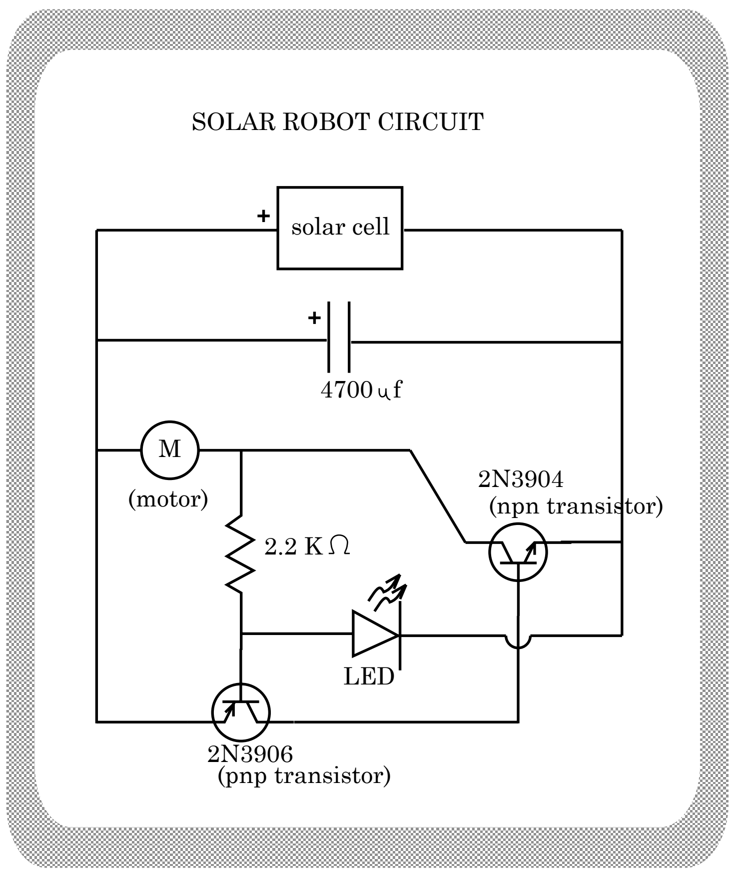


FIGURE 15.28

b.) This will occur if two conditions are met:

i.) The first condition is that the solar cell must charge up the capacitor.

ii.) The second condition is that the *base/emitter* voltage of the *pnp* transistor (look back at Figure 15.28) gets to .6 volts so that the *pnp* transistor can switch *on*. When this happens, the *pnp's* collector current will feed into the base of the *npn* transistor. In doing so, the *npn transistor* will turn *on*. With the *pnp on*, the capacitor will discharging *through the motor* (Figure 15.29 again). In doing so, the motor's shaft will turn, at least until the discharging capacitor runs out of charge, and we will have the making of a robot.

c.) The trick, therefore, is to turn *on* the *npn* transistor once the capacitor has charged up.

2.) In a little more detail, this is how it works.

a.) Look at Figure 15.30. Note that points A, B, C, and E all have the same voltage.

b.) Initially, before light is allowed to fall on the solar cell, the

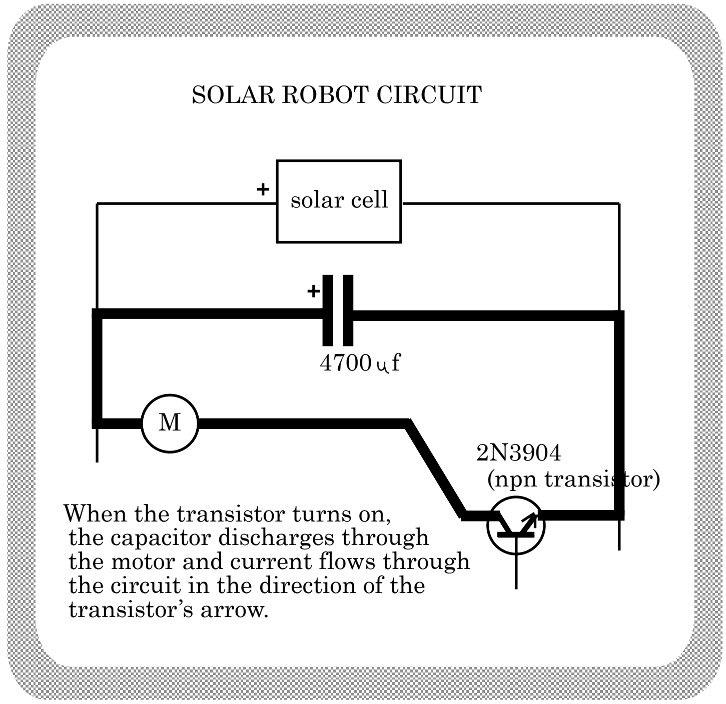


FIGURE 15.29

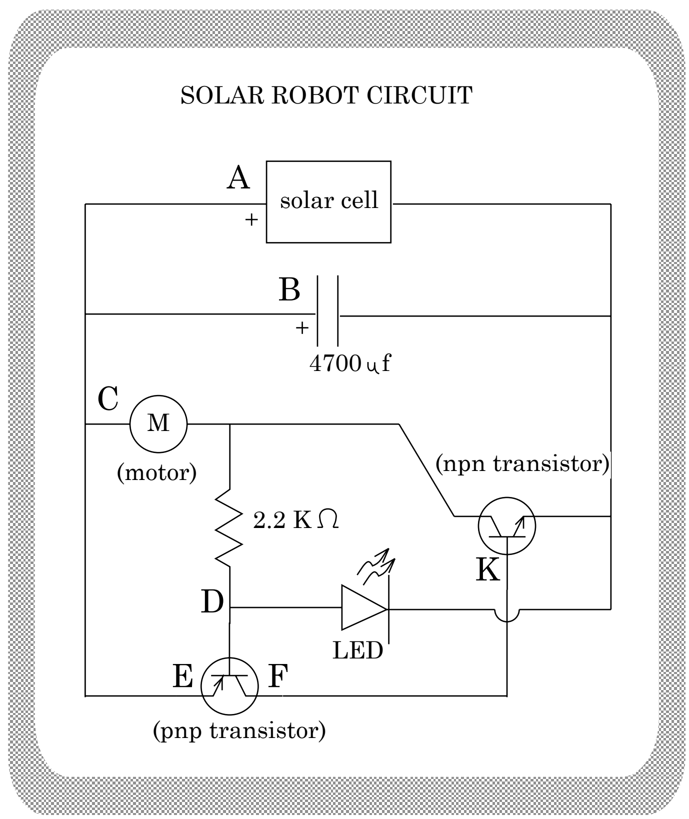


FIGURE 15.30

capacitor is uncharged and voltages at points A, B, C and E are all zero.

c.) With light on the solar cell, the capacitor begins to charge and the voltage at points A, B, C and E begin to increase. This generates a current into the emitter of the *pnp transistor* at point E, some of which continues on through the collector at point F and some of which passes out through the base moving toward D.

d.) As the capacitor's voltage continues to increase, the current out of the *pnp's* base increases. As it does, both the *base/emitter voltage* and the *base/collector voltage* increase. When the *base/emitter voltage* hits the infamous .6 volts, the transistor's current characteristics blossom and the transistor turns *on*.

e.) With significant current now flowing out of the *pnp's collector* at F and into the *npn's base* at K, the *npn* transistor turns *on*.

f.) With the *npn* transistor turned *on*, we now have access to the current path pointed out in Figure 15.29. The capacitor dumps all of its charge through the motor, and the motor's shaft rotates.

g.) The rotation continues until the capacitor has dumped nearly all of its charge. At that time, the voltage at A, B, C and E are nearly back to zero and the *pnp* transistor turns *off*. This, in turn, turns the *npn* transistor *off*.

h.) With all of the transistors *off*, the capacitor again begins to charge up and the cycle start over again. Thus, the motor goes, then stops, then goes, then stops, etc.

i.) If the shaft of the motor is attached to some kind of wheel assembly, the motor can be used to motivate a cart-like structure to move. That, ultimately, is what you will be trying for in lab.

Minor Note: The resistance associated with the motor is not constant. The net effect of this is that it is hard to get the motor started but easy to keep it going once in motion. The consequence of this is that the capacitor must charge up beyond the voltage that would merely *keep* the motor running in order to *get* the motor running. This extra charge on the capacitor allows the motor to run longer than it normally would in a fixed resistance scenario. (This is not terribly important. It is just an interesting side note.)

QUESTIONS & PROBLEMS

15.1) What is the difference between a conductor and a semi-conductor?

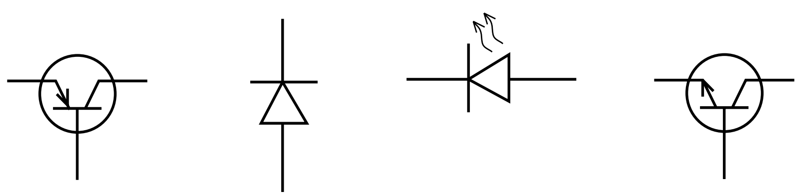
15.2) What is the difference between an *n-type* semi-conductor and a *p-type* semi-conductor?

15.3) How are diodes built?

15.4) Why do LEDs give off light?

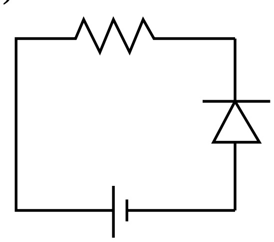
15.5) How are transistors built?

15.6) Identify the electrical symbol shown below.

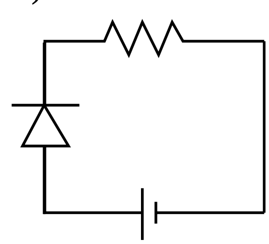


15.7) In the two circuits shown, the diode is silicon, the resistor's resistance is 20 ohms, and the power supply is an 8 volt source.

a.)



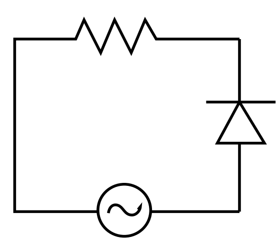
b.)



a.) Will current flow through the first circuit shown? If not, why not? If so, how much?

b.) Will current flow through the second circuit shown? If not, why not? If so, how much?

15.8) For the circuit shown:



a.) What will the *voltage versus time* graph look like for the power supply in the circuit?

b.) What will the *voltage versus time* graph look like for the resistor in the circuit?

15.9) What is a half-wave rectifier? That is:

a.) How is it built?

b.) What might it be used for?

c.) If you placed a half-wave rectifier in a circuit with an AC power supply and a resistor, what would the graph of the current through the circuit look like (don't mess with actual numbers--just make this a general sketch)?

15.10) What is a full-wave rectifier? That is:

a.) How is it built?

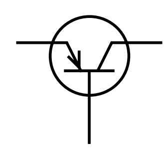
b.) What is its output in an AC circuit look like and what might it be used for?

c.) If you placed a half-wave rectifier in a circuit with an AC power supply and a resistor, what would the graph of the current through the circuit look like (don't mess with actual numbers--just make this a general sketch)?

15.11) It is not unusual to place a capacitor across the load of a full-wave rectifier. What does this do?

15.12) What is ripple? (No, I don't mean the wine!)

15.13) For the transistor shown:

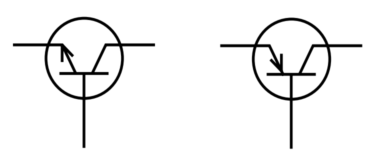


a.) Name the parts (i.e., the leads).

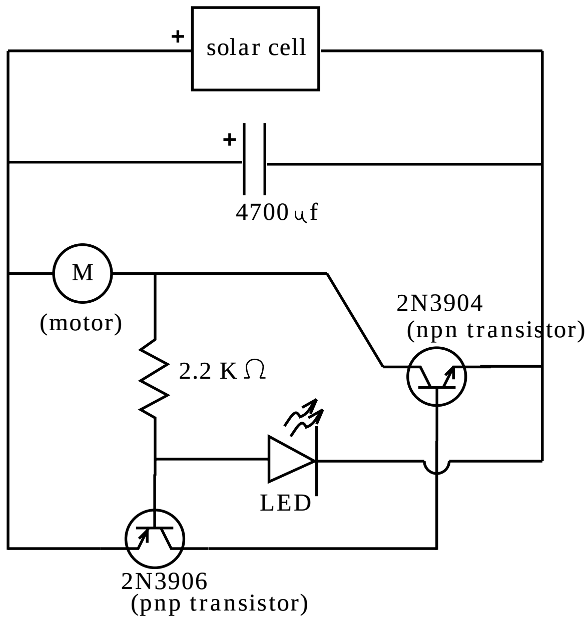
b.) In what direction would current flow if it could flow through the upper section?

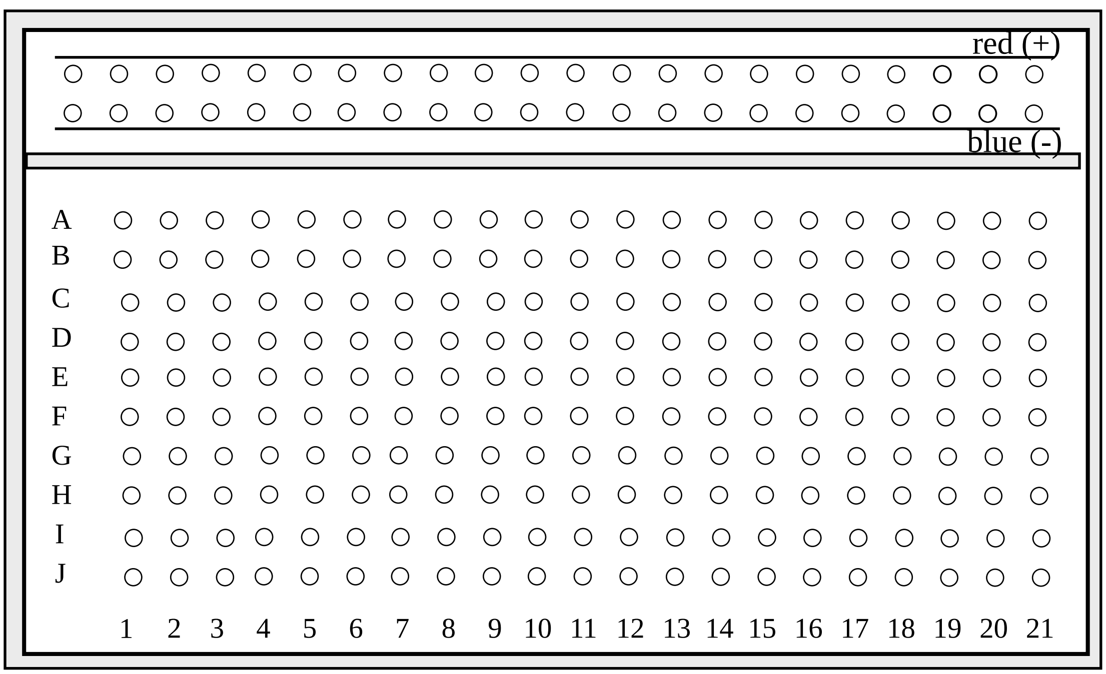
c.) Create a circuit in which current will flow through the upper section.

15.14) For each of the devices shown, determine what the base's bias must be (i.e., positive or negative), relative to the emitter, for current to pass through the upper section.



15.15) The circuit on the next page has two transistors, a solar cell, a capacitor, a motor, a resistor, and an LED. Assuming you take the solar cell to be your power source, use the sketch of a breadboard provided to sketch out how you would breadboard this circuit. (In fact, this exercise will be more useful than you think--you will have to do this in real life as you prepare to wire your robot circuit.)


+
solar cell
+
4700 uf
M
(motor)
2N3904
(npn transistor)
2.2 K Ω
LED
2N3906
(pnp transistor)


red (+)
blue (-)
A
B
C
D
E
F
G
H
I
J
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21