Smart-Lighting Sensor Circuit

Betty Lise Anderson

Purpose:

In a smart-lighting system, the idea is that when the room is bright enough due to light coming in through the window, for example, the rooms lights don't need to be on. If it gets dark, or rains, or in some way diminishes the ambient light in the room, the light should come on automatically. The purpose of this project is to build and understand a simplified version of a control ciruit that performs this function. We'll use it to turn an LED and off, to demonstrate the principle.

Overview

Figure 1 shows a block diagram for the circuit. The first element is a "rail splitter." It divides the battery voltage in half, which will serve as an input to the second component, a transimpedance amplifier. The light sensor provides the other input. The third stage is a comparator circuit, which compares two inputs, and outs a high or low voltage depending on which input is higher, and finally the LED that is turned on or off.

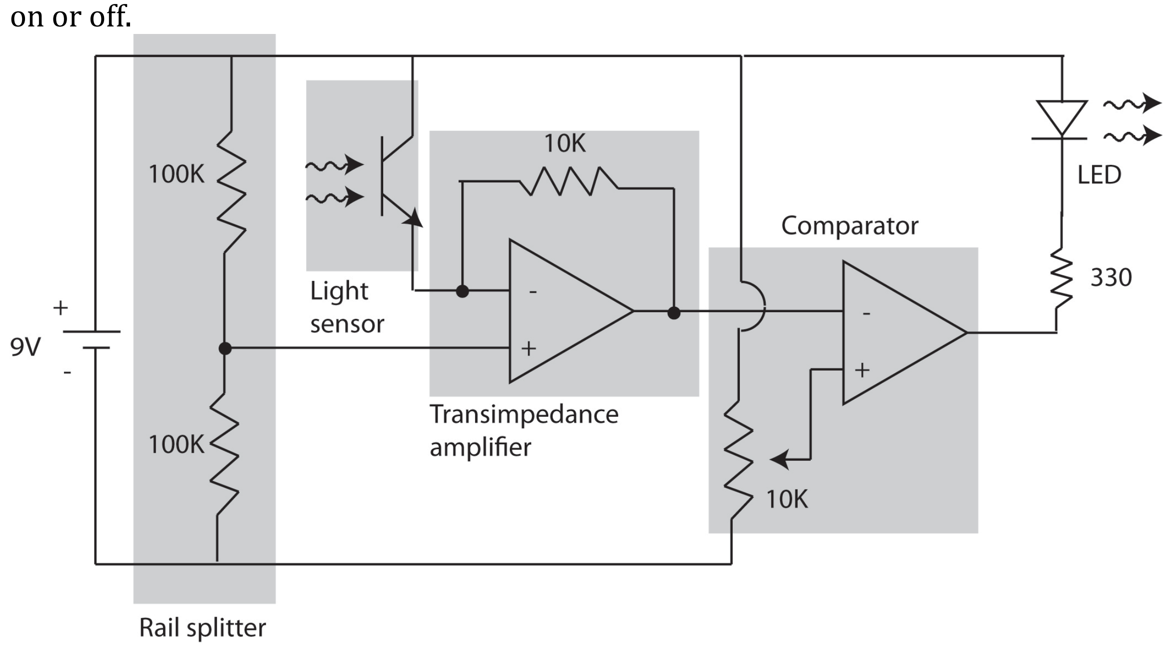


Figure 1. A block diagram of the circuit.

How it works

Let us examine the operation of each block in turn. First, the rail splitter. It consists of two 100 kΩ resistors. This is also known as a voltage divider, Figure 2. The input voltage V_{in} creates a current that flow through the two resistors *R1* and *R2*. Recall from Ohm's Law that *V=IR*. Since the same current *I* flows through both resistors (it has no where else to go!), the voltage across *R*1 *is I·R1* and the voltage across *R2* is *I·R2*. These two must add up to V_{in}, so

$$V_{in} = IR_1 + IR_2 = I(R_1 + R_2)$$

Now, the output voltage is just *I·R2*, or

$$V_{out} = IR_2$$

If we divide one equation by the other, we get

$$\frac{V_{out}}{V_{in}} = \frac{IR_2}{I(R_1 + R_2)} = \frac{R_2}{R_1 + R_2}$$

or

$$V_{out} = \left(\frac{R_2}{R_1 + R_2}\right)V_{in}$$

In our circuit, *R1*=*R2*=100KΩ, so V_{out} is ½ V_{in}. Thus we have split the 9V "rail" into two equal voltages, and 4.5 V appears at the input to the next stage, the transimpedance amplifier. We will use the 4.5 V as a reference voltage.

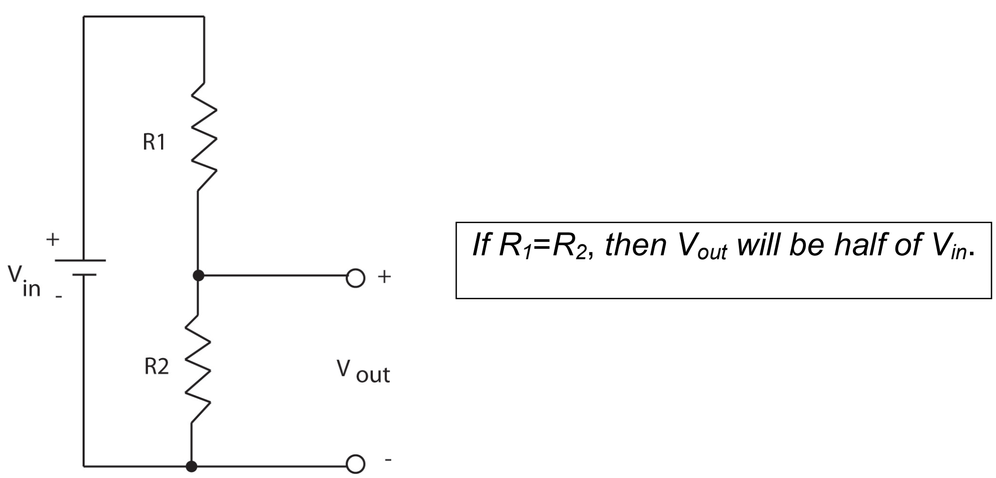


Figure 2. A voltage divider serves as a rail splitter.

Operational amplifier (Op amp)

The next two stage use an operational amplifier, an amazing versatile and useful integrated circuit. The circuit symbol, Figure 3, is a triangle, with two inputs, positive and negative, and an output. The internal guts of the "op amp" are not important. What we need to know is that an ideal op amp tries to amplify the difference in voltages between the two inputs. The gain is huge, so even a small difference in voltage between the positive and negative inputs results in a large output.

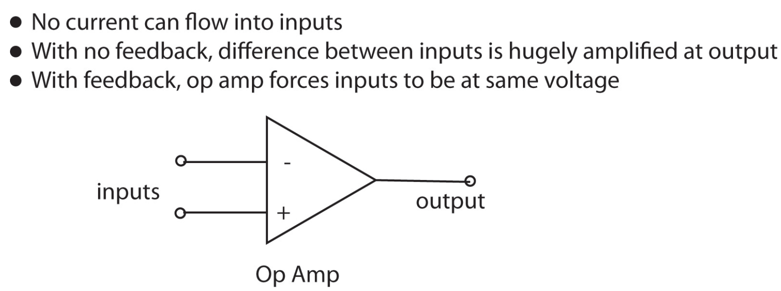


Figure 3. The op amp.

Op amps also have the property that their input impedance (resistance) is huge, so essentially no current flows into the inputs.

They have another property, however, that make them even more useful: if there is some kind of connection between the output and the input, called feedback, then the op amp tries to force the two inputs to be at the same voltage.

Summary of ideal op amp properties:

- No current can low into the inputs
- If there is feedback (a path from the output back to the input) then the two inputs are forced to the same voltage
- If there is no feedback, the output is a very large number times the difference in the input voltages. If the amplification is factor G (for "gain"), then

$$V_{out} = G\left(V_+ - V_-\right)$$

where V_+ and V_- are the voltages at the corresponding inputs.

We will use two op amps, in two different configurations. The first will be used as a transimpedance amplifier, which converts a current to a voltage, and the second will be used as a comparator.

Transimpedance amplifier

Figure 4 shows the second stage of the circuit, the transimpedance amplifier. There is a light sensor, in this case a phototransistor. When light shines on, a current *I* is produced. We want to generate a voltage, however, which is what this circuit will do.

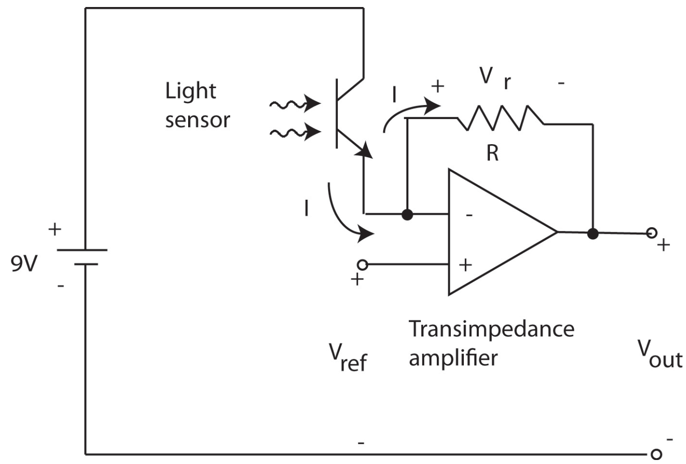


Figure 4. The transimpedance amplifier.

Recall that no current can flow into the op amp. The inputs have very nearly infinite impedances. Therefore the photocurrent is forced to flow through the feedback resistor *R*. When current flows through a resistor, a voltage is generated (*V=IR*, Ohm's Law again). Let's analyze this circuit.

We remember that when there is feedback (some electrical path from the output back to the input), then the op amp forces the voltage at the two inputs to be the same. The positive input is already fixed at V_{ref}=4.5 V from the rail splitter. Because there is a feedback resistor, we know that the negative input is also at 4.5 V.

Now, the photocurrent I flows through the feedback resistor in the direction shown. It generates a voltage V_r across the resistor. Next, we apply Kirchoff's Voltage Law, which says that all of the voltages summed around a loop sum to zero.

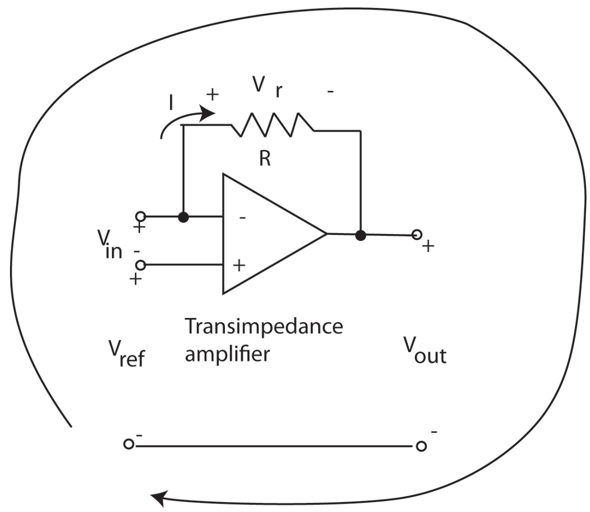


Figure 5. Applying Kirchoff's Voltage Law.

Let's look at Figure 5, which shows a loop. The rule is, you pick a direction, say, clockwise, and for each voltage, if you come to the positive sign first, the voltage is positive, and if you come to the negative sign first, it's negative. Starting with V_{ref}, we encounter the negative sign first, going clockwise, so it is negative. The next one, V_{in}, is also negative (actually, we know it is zero, because the two inputs are forced to the same voltage). The voltage $V_{r,}$, however, is positive. We thus end up with the equation

$$-V_{ref} - V_{in} + V_r + V_{out} = 0$$

Knowing that V_{in} =0 and solving for the output, we find

$$V_{out} = V_{ref} - V_r$$

But, V_r=*IR,* so we have

$$V_{out} = V_{ref} - IR$$

If the room is dark, and there is no photocurrent, then V_{out}=V_{ref}. If the light increases (say, you open the curtains), then the photocurrent *I* increases, which increases V_r, and that *decreases* the output voltage V_{out}. If it gets darker, the output voltage goes up again. That output voltage serves as the input to the final stage, the comparator.

Why is this circuit called a "transimpedance amplifier?" Because it converts an input current to an output voltage. That is what a resistance or impedance does also, because a current flowing through a resistor also produces a voltage. Then why did we use an op amp instead of a resistor? Because the op amp will maintain the proper voltage at the output even if we connect other stuff to it. If we need additional current to drive the next stage, it comes out of the amplifier via the actual guts of the op amp. A simple resistor, if additional current is needed, that would change its voltage and change the output.

The comparator

Our goal is a circuit that will turn the lights on when the room gets dark. We already saw that if the room gets darker, the voltage out of the transimpedance amplifier increases. At some point, we want the circuit to switch. And, we want to be able to adjust that point. A comparator is an op amp circuit that will switch its output voltage based on the different between the two input voltages.

Figure 6 shows the comparator circuit. Notice this one does *not* have feedback. Therefore, it doesn't force the "differential input voltage" (to throw in some good jargon) to zero, but rather amplifies that voltage. By a lot.

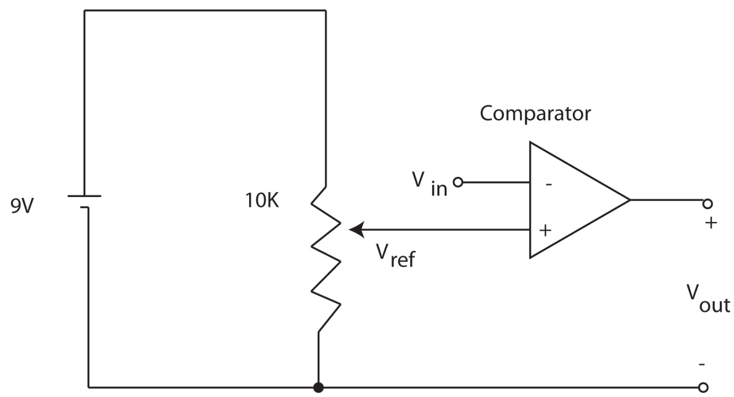


Figure 6. The comparator

The resistor in this circuit is a variable resistor, or potentiometer ("pot" for short). It is a three-terminal device. The lead with the arrow on it is called the "wiper." Remember the voltage divider from the rail splitter section? This is the same thing, but by moving the wiper (usually by turning a knob or screw), you vary the values of R_1 and R_2, and thus change the voltage at the wiper. We'll use this as our "thermostat" for setting the lighting threshold at which we want our room lights to come on. We need to be able to adjust this since rooms are different and people are different.

In this circuit, the input signal V_{in} is actually the output from the transimpedance amplifier. It varies with the ambient light condition. Let's suppose that V_{in} is greater than V_{ref}.. The op amp, which doesn't have feedback, amplifies that difference. The gain is approximately G=a zillion. Remember that when there is no feedback,

$$V_{out} = G\left(V_+ - V_-\right)$$

The signal voltage V_{in} is going to the negative input, so $V_- = V_{in}$. The reference voltage is connected to the positive input, or $V_+ = V_{ref}$. So, we have

$$V_{out} = G\left(V_{ref} - V_{in}\right)$$

Suppose the input voltage is 4 V. Remember this can only happen when there is current flowing through the sensor meaning the room is already bright. We know the reference is 5V, so we have

$$V_{out} = G\left(V_{ref} - V_{in}\right) = G(5-4) = G$$

The output voltage shoots up, Figure 7--but wait! It can't go any higher than 9 Volts, because that's the voltage of the battery. So the output shoots up to 9V, and stays there.

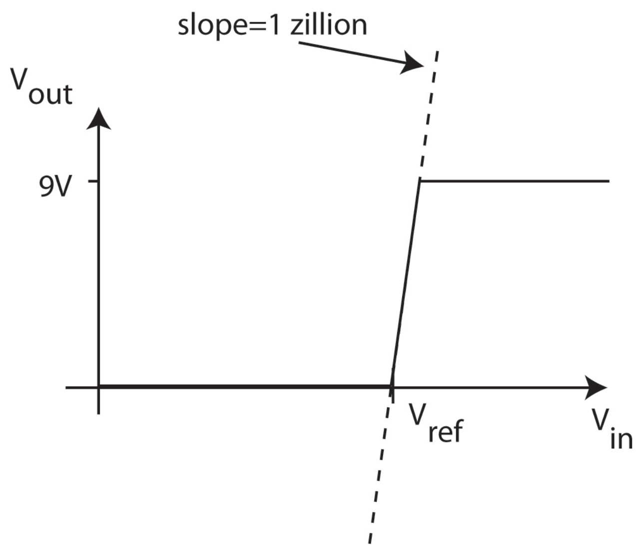


Figure 7. The transfer function of the comparator.

If the input goes lower than the reference, the op amp sees a negative differential input and tries to amplify it to a huge negative number. But, it can't go lower than zero in our circuit because we have no negative voltage source, so it's stuck at zero.

Could you balance somewhere in the middle? Well, only if the differential voltage were very, very small. Realistically even if you could turn the knob on the reference voltage to that spot, it wouldn't stay there because of temperature changes, noise in the circuit, evil spirits, and so forth. Thus, the comparator output is either high or low. The output is high when the room is bright, and low when the room is darker.

OK, we're almost down the wire.[1] We want the light to come on when it gets dark. When it gets dark, the output of the transimpedance amplifier goes up, so it may be higher than the reference voltage. When the input is higher than the reference, the difference voltage V_{+}-V_{-} will be negative, and the output will go low. We want the LED light to come on when the output is low.

[1] Eletrical engineering humor

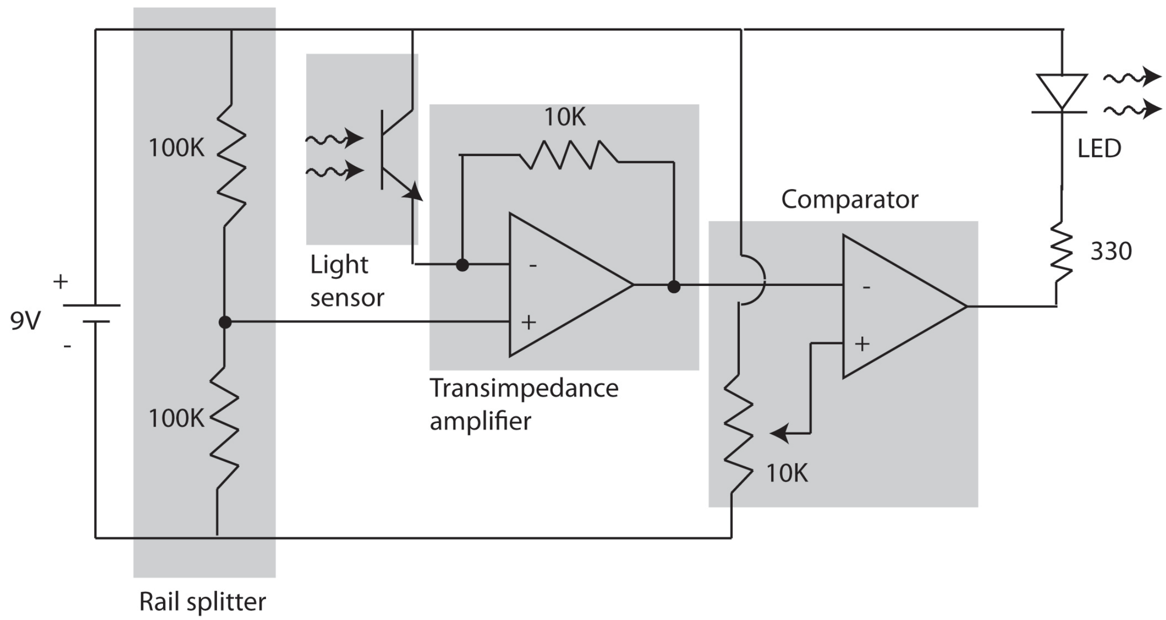


Figure 8. The complete circuit.

Figure 8 shows the last piece. The output drives an LED, or light-emitting diode. A diode is a device that allows current to flow in one direction, but not the other. The circuit symbol is a triangle with a line. The current is allowed to flow in the direction of the point of the triangle, but the line reminds us that the current can't flow back the other way.

Since we want the light to come on when the output is low, we connect the LED as shown in the figure. When the output is low, it is at 0V, and current can flow through the LED, which will light up. The LED will have about 1.5V across it when it's on, so the 300 Ω resistor is there to limit the current and keep the LED from burning up. When the comparator output goes high, there are 9V volts at the output, and the LED is also connected to 9 volts, so no current flows and the LED turns off.

In the next section, we'll see how to build this circuit.

Building the circuit

The schematic diagram shown in Figure 8 shows how the circuit works, but it doesn't tell you the complete picture. For example, the op amp is an integrated circuit that has to have connectsion to the power supply (battery), which are not shown. So in this section, we'll show the details.

A complete parts list is given in Appendix A.

A solderless breadboard, Figure 9, provides a convenient way to wire up circuits quickly. It is full of holes with electrical connections inside. First, all the holes along one of the green lines are connected together. That is called a “buss,” and it’s usually used for something you need to make lots of connections too, like the battery. This board is typical in that it has four separate busses.

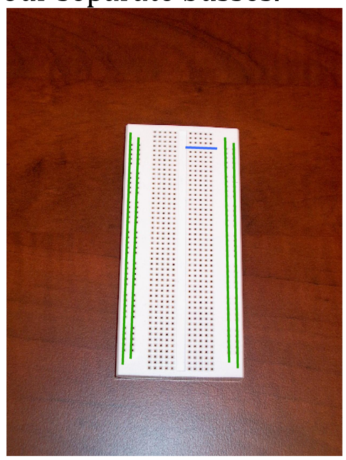


Figure 9. The breadboard. The green lines indicate the busses, and the blue line is a node.

The blue line in the figure indicates one “node.” There are five holes, and if you stick a wire in one of those holes, it’s automatically connected to the other four holes. There are separate nodes on either side of the central channel.

Connecting the busses

Let’ start by connecting the batter to the busses. It will be handy to have positive and negative busses on both sides of the breadboard so we’ll also connect them with wire. Red is positive and black is negative.

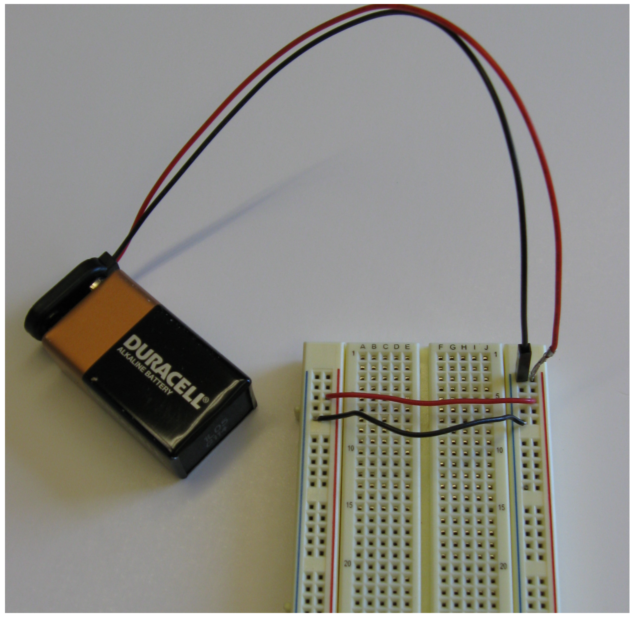
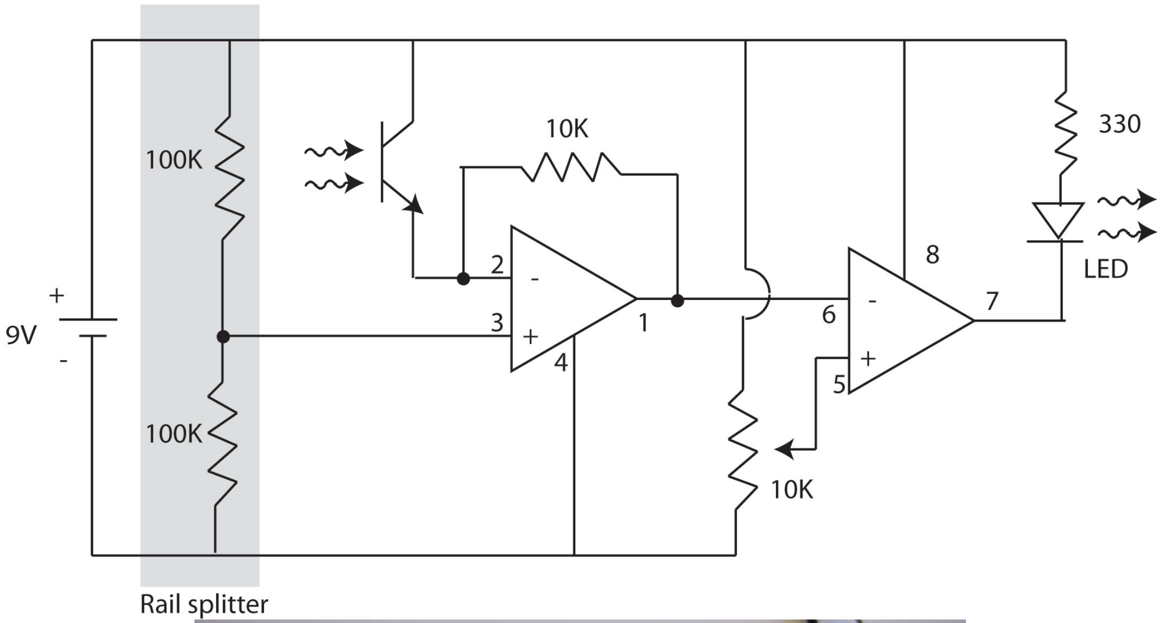


Figure 9. Connecting the battery.

Rail-splitter

Next, disconnect the battery. You shouldn't wire a circuit with the battery connected. Let's connect the rail-splitter, highlighted in Figure 10. The two resistors are 100 KΩ, The stripe colors are brown, black, yellow. Appendix B has a chart of the resistor color codes. The gold band just means "5%" meaning the value is guaranteed to be within 5% of the nominal value.

We'll connect up that loose wire in a later step.



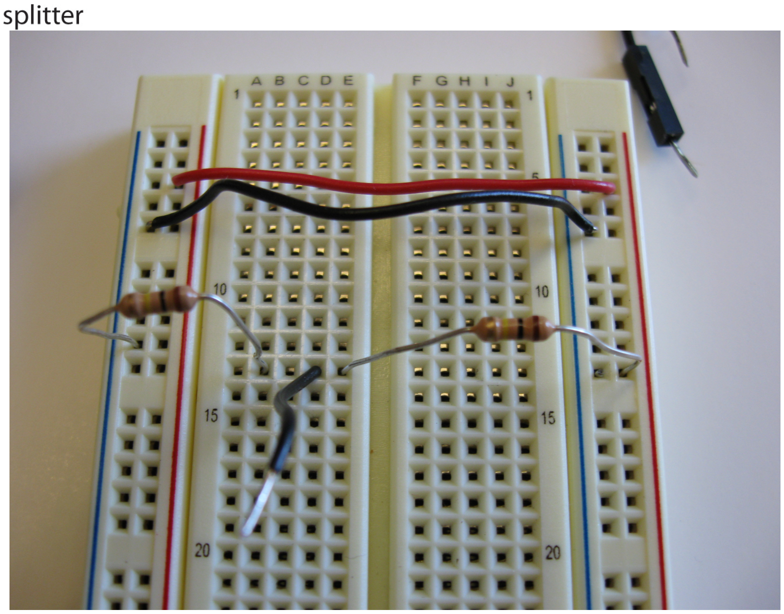


Figure 10. The rail-splitter (voltage divider).

The dual op amp

Next, we will put in the op amps. We are using an LM 358 integrated circuit, which actually has *two* op amps on on chip, most convenient. Figure 11 shows a photograph and a diagram. This is an 8-pin DIP (dual inline package, meaning two rows of pins). The diagram shows not only what inside (schematically) but also shows the pinout and how the pins are numbered. Notice that the package has a divot near one end. Sometimes it's a dot. In the diagram, the dot indicates which end is "up" so we know how to count the pins. The pins always start in the upper left hand corner, go down one side and up the other.

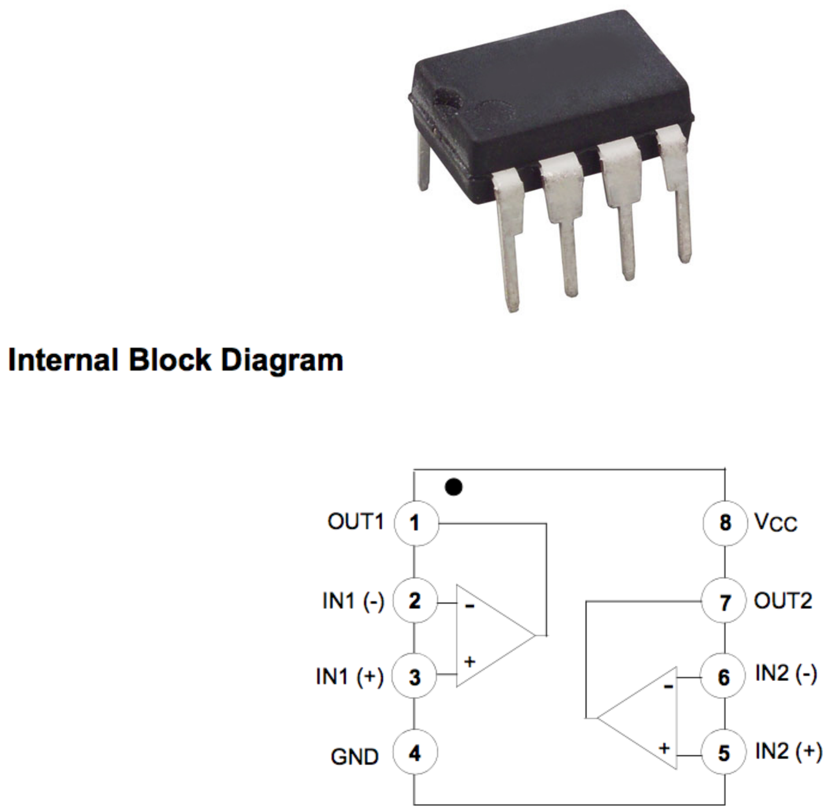


Figure 11. The DIP. http://alan-parekh.vstore.ca/controller-chip-pi-118.html

We can see the two op amps, with their inputs and outputs, but what are V_{cc} and *GND?* The label V_{cc} is electrical engineering code for "power supply," specifically a positive power supply.[2] This is one of those hidden connections. It's not shown in the schematic, because electrical engineers know they have to be there. Figure 12 show a connection from Pin 8, V_{cc}, to the positive buss. Pin 4 is GND, or ground, which is the negative buss in this case.

[2] If you want to know why, we have some great courses you can take.

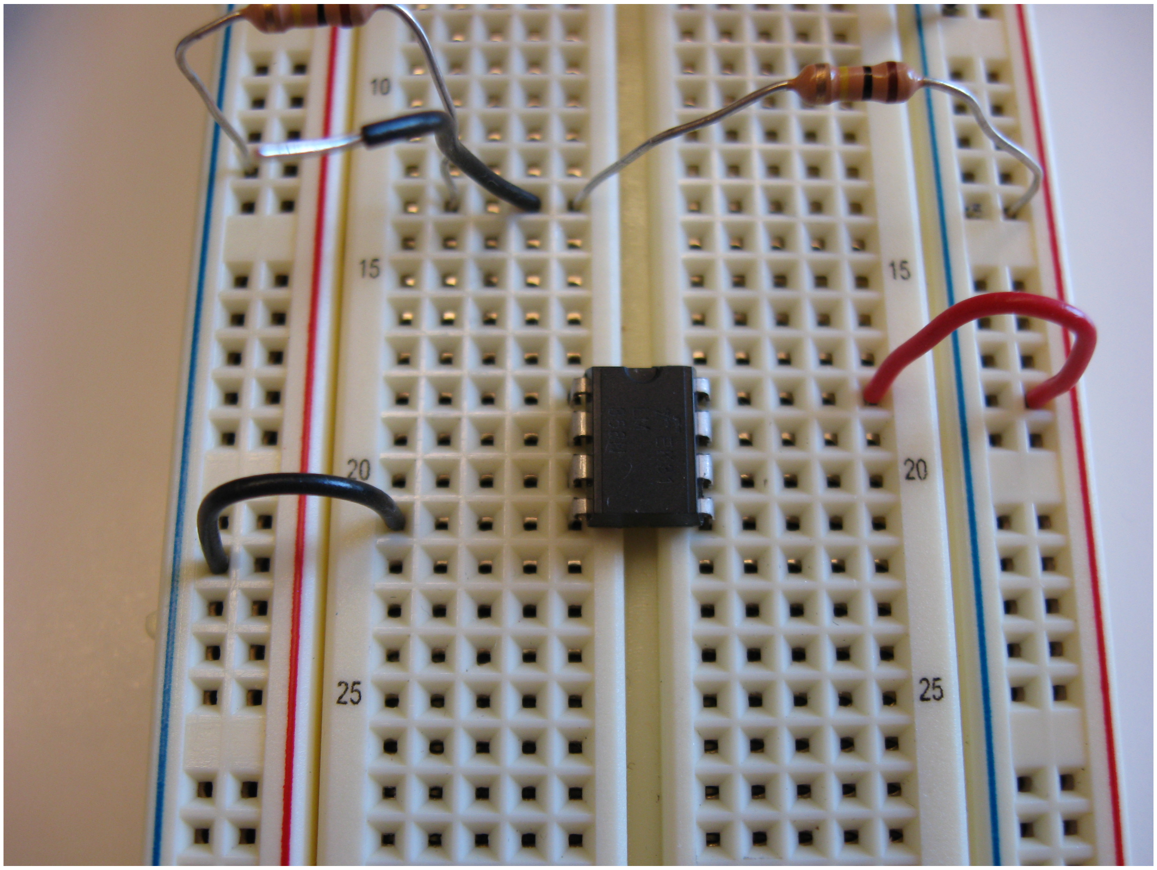


Figure 12. Connecting the power supply and ground for the chip.

The transimpedance amplifier and light sensor

Next, let's hook up the transimpedance amplifier and light sensor, Figure 13. We'll use the first op amp on the chip for this stage, so we'll use pins 1, 2, and 3. From the schematic, we see that the output of the rail splitter should be connected to the positive input, or pin 3.

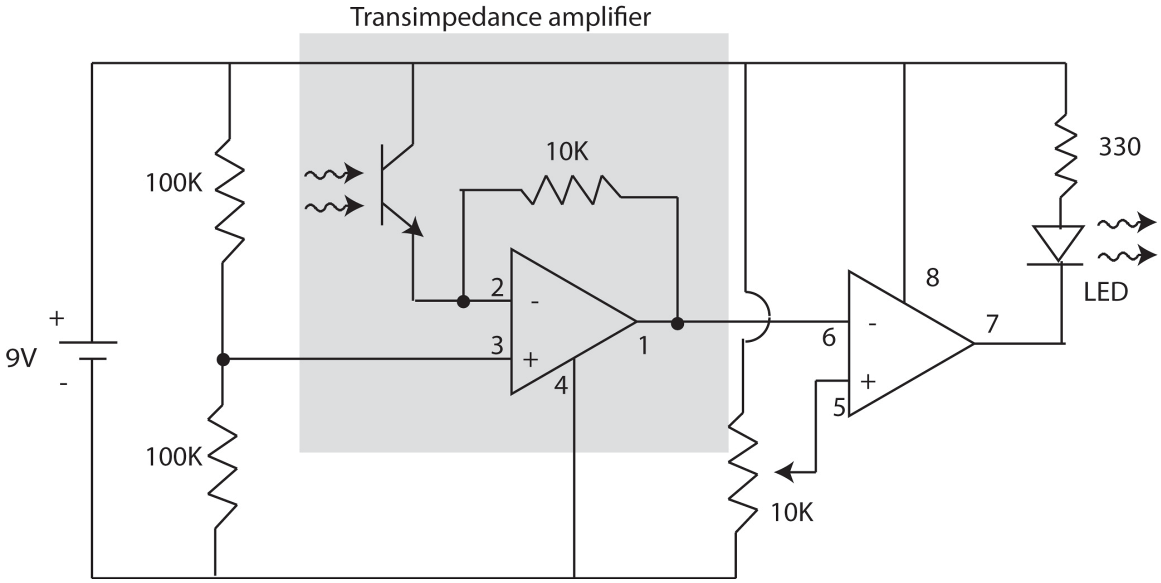


Figure 13.

The light sensor is connected to the other input. Figure 14 shows a drawing of the light sensor, a phototransistor. You will notice that one lead is shorter than the other. That tells us which lead is which.

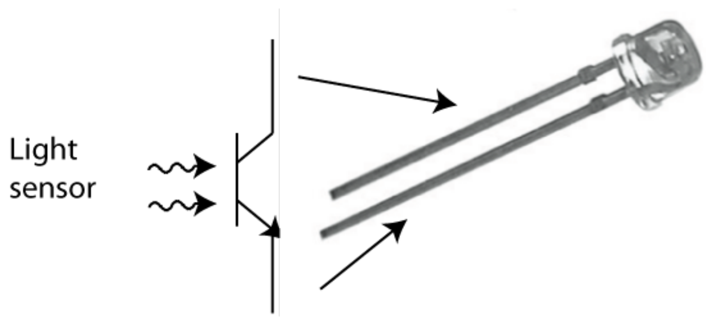


Figure 14. The light sensor.

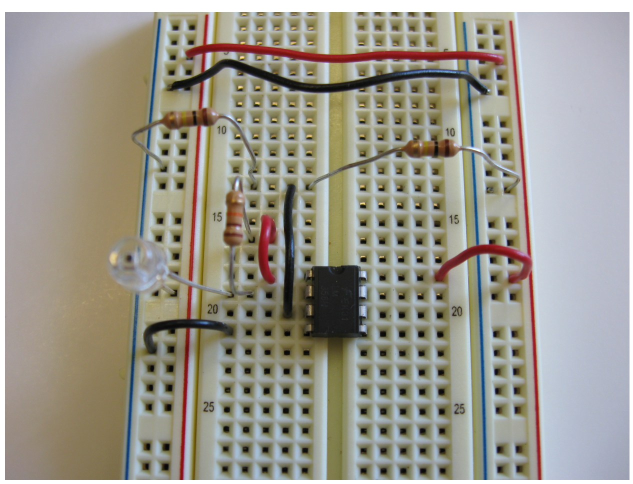


Figure 15. The transimpedance amplifier.

Figure 15 shows the physical connections, and the schematic is repeated here for you to compare. The feedback resistor is 10 KΩ, or brown, black, orange. It is connected between pins 1 and 2 using a spare node and a wire.[3] The light sensor is connected between the positive buss and pin 3. The long lead of the phototransistor goes topin 3 of the op amp.

The comparator

For the comparator circuit, we will introduce the potentiometer., Figure 16.

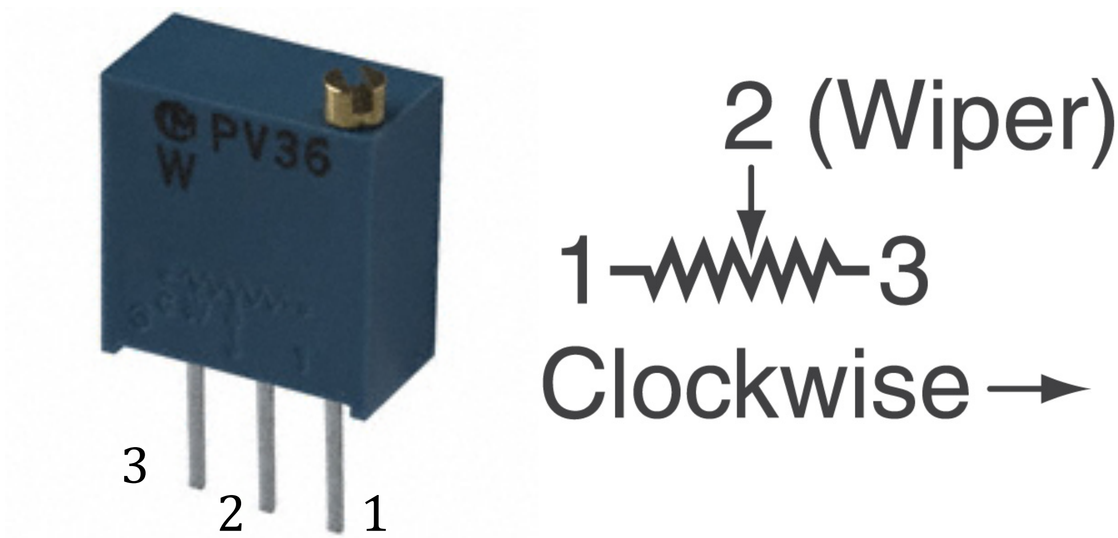


Figure 16. A trimpot (trimmer potentiometer)

From the schematic, we see that Pin 1 is connected to positive, Pin 3 is connected to negative, and the wiper is connected to the positive input of the second op amp. The other input is connected to the output of the previous stage.

[3] You can also just connect the resistor between 1 and 2 directly, without the wire, but it makes things little crowded. Electrically, it doesn't matter.

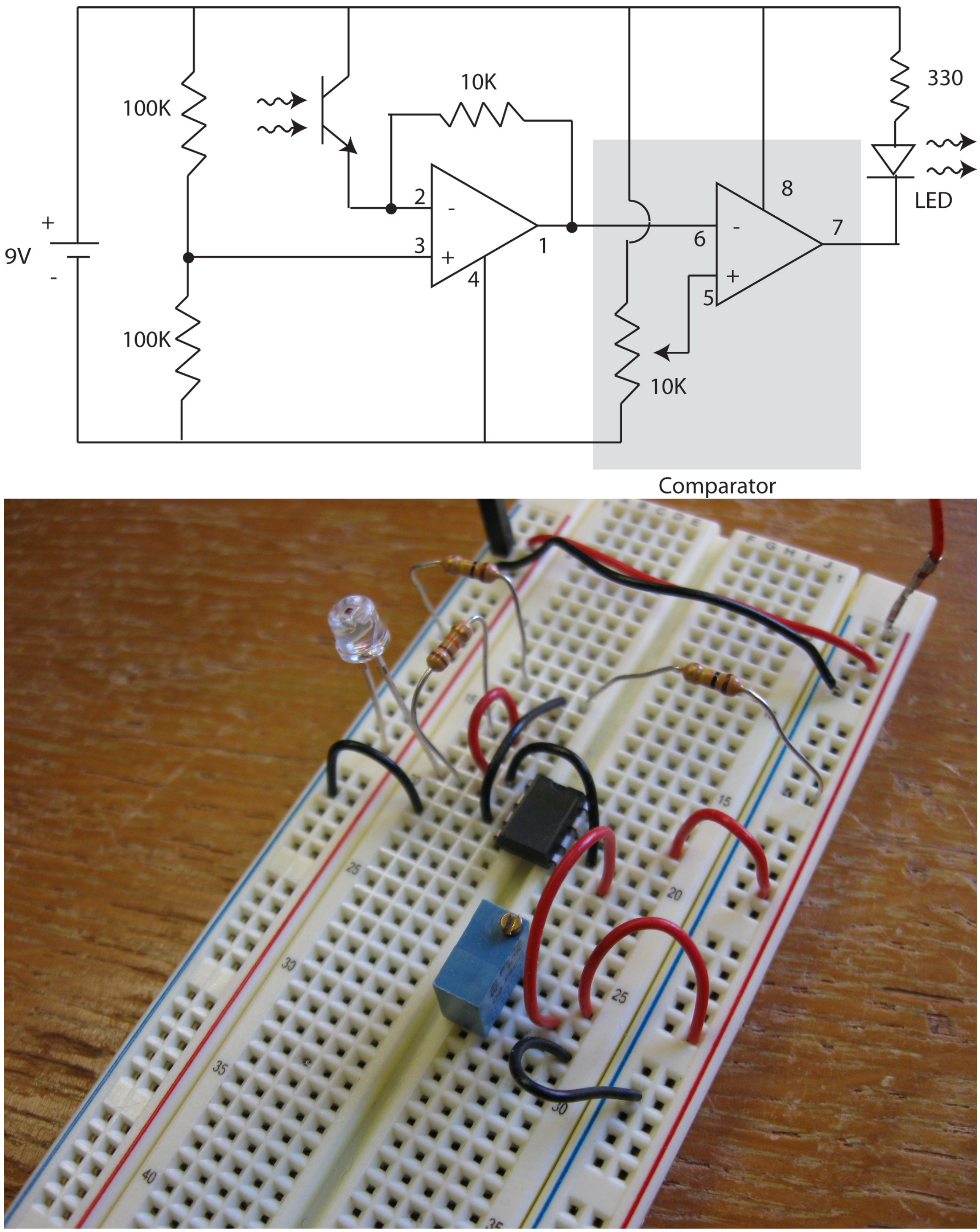
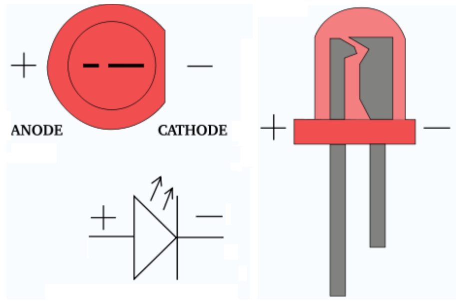


Figure 17. Buidling the comparator.

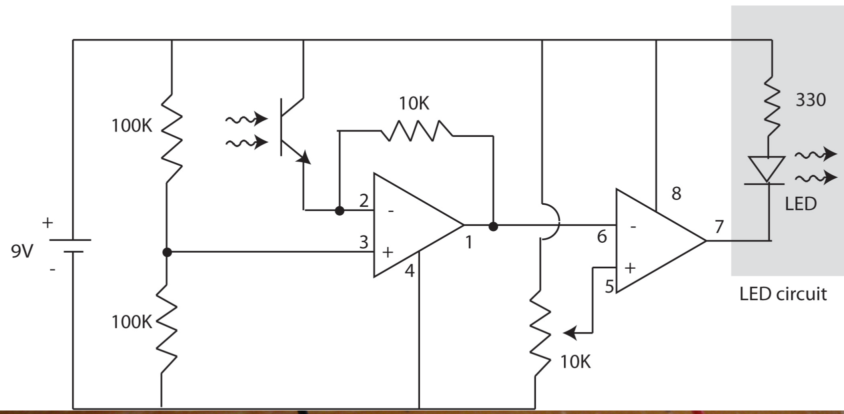
The LED circuit

All that's left is to connect the LED at the comparator output. The LED has a package similar to the light sensor, with one lead longer than the other, Figure 18. There is also a flat on the flange. The flat and the shorter lead correspond to the cathode. The resistor in this circuit is 330 Ω, or orange, orange, brown.



http://www.societyofrobots.com/electronics_led_tutorial.shtml

Figure 18. Polarity of the LED



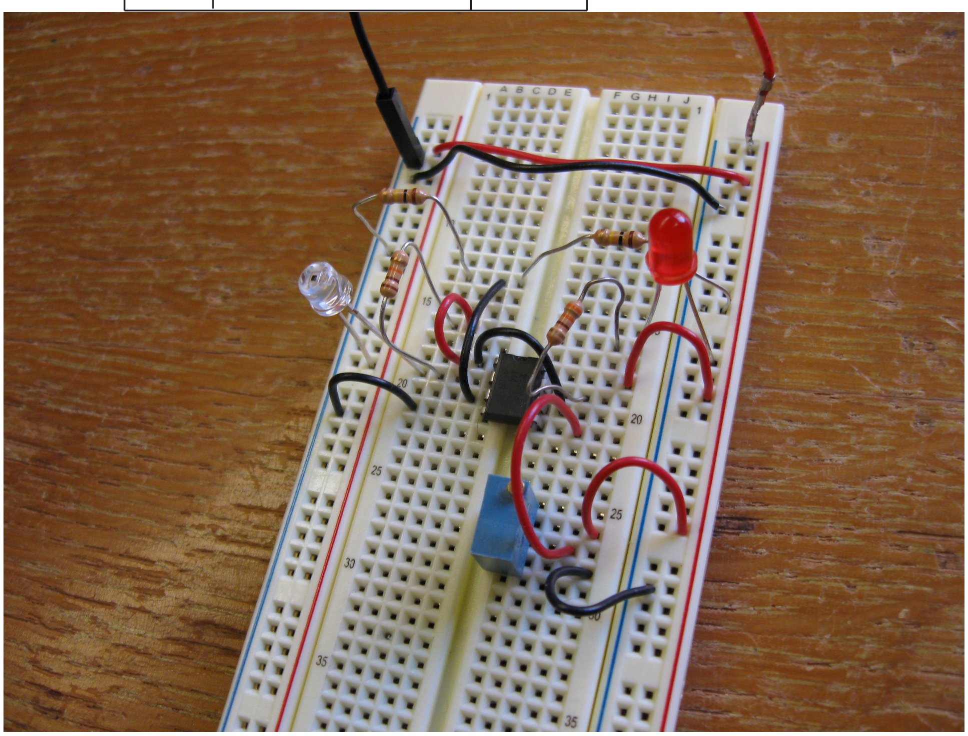


Figure 18. The output LED circuit is added.

Testing the circuit

Now you're ready to test the circuit. Don't forget to reconnect the battery. When you turn the circuit on, the LED may or may not come on. It depends on the brightness of the room and where the wiper is on the potentiometer, which you usually don't know. This is a 25-turn pot, by the way. Experiment with adjusting the pot until the light turns on (or off, as the case may be). Then try covering the sensor to simulate dark conditions.

Trouble shooting

LED never comes on	Check polarity of LED
LED never goes off	Check polarity of light sensor
Battery gets hot	DISCONNECT IMMEDIATELY. There is a short circuit; check wiring.
Chip gets hot	DISCONNECT BATTERY IMMEDIATELY. Check wiring. However, if this happens, the chip may be destroyed.

Appendix A. Parts list

Parts list

Part	P/N	Source	Qty	Unit Cost
Breadboard, solderless	20601	Jameco	1	$5.49
Operational Amplifier	23966*	Jameco	1	$0.25
Ambient light sensor	751-1059-ND	Digikey	1	$0.43
LED, red diffuse 5 mm	754-1264-ND	Digikey	1	$0.09
Potentiometer, trimmer 10K**	490-2875-ND	Digikey	1	$1.33
Resistor, 100KOhm, ¼ Watt, Carbon film, 5%	100K-QBK-ND	Digikey	2	$0.06
Resistor, 10K, Ohm, ¼ Watt, Carbon film, 5%	10KQBK-ND	Digikey	1	$0.06
Resistor, 330 Ohn, ¼ Watt, Carbon Film, 5%	330QBK-ND	Digikey	1	$0.06
Battery, 9V	P647-ND	Digikey	1	$1.77
Battery Snap, 9V	109154	Jameco	1	$0.29
Trimpot adjustor (optional) (screwdriver)	153315	Jameco	1	$1.75 (opt)
TOTAL				$11.64

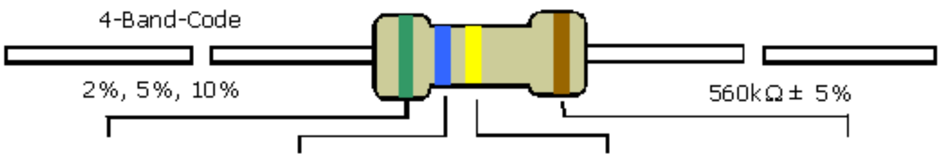
*Any operational amplifier that starts with LM358 will work, as long as it's an 8-dip (8-pin dual in-line package, 8 pins in two rows)
** Any 10K potentiometer will do, but it's helpful to have one that has multiple turns- this one has 25. Makes it easier to adjust.

Appendix B. Resistor color codes.

http://www.elexp.com/t_resist.htm

The colors on a resistor are used as follows: the first two stripes give the first two numbers, as in green blue= 56. The third stripe give the exponent in 10^x. In this example, the exponent is 5, so we have

56×10^5 or 560 kOhm.



COLOR	1st BAND	2nd BAND	3rd BAND	MULTIPLIER	TOLERANCE	
Black	0	0	0	1Ω		
Brown	1	1	1	10Ω	± 1%	(F)
Red	2	2	2	100Ω	± 2%	(G)
Orange	3	3	3	1KΩ		
Yellow	4	4	4	10KΩ		
Green	5	5	5	100KΩ	±0.5%	(D)
Blue	6	6	6	1MΩ	±0.25%	(C)
Violet	7	7	7	10MΩ	±0.10%	(B)
Grey	8	8	8		±0.05%	
White	9	9	9			
Gold				0.1	± 5%	(J)
Silver				0.01	± 10%	(K)

Electronix Express / RSR **1-800-972-2225**

http://www.elexp.com ***In NJ 732-381-8020***

Appendix C Data sheets

Ambient Light Sensor

20118

DESCRIPTION

TEPT5700 ambient light sensor is a silicon NPN epitaxial planar phototransistor in a T-1¾ package. It is sensitive to visible light much like the human eye and has peak sensitivity at 570 nm.

FEATURES

- Package type: leaded
- Package form: T-1¾
- Dimensions (in mm): Ø 5
- High photo sensitivity
- Adapted to human eye responsivity
- Angle of half sensitivity: φ = ± 50°
- Compliant to RoHS Directive 2002/95/EC and in accordance to WEEE 2002/96/EC

Note

** Please see document "Vishay Material Category Policy": www.vishay.com/doc?99902

APPLICATIONS

- Ambient light sensor for control of display backlight dimming in LCD displays and keypad backlighting of mobile devices and in industrial on/off-lighting operation

PRODUCT SUMMARY			
COMPONENT	**I_{PCE} (mA)**	**φ (deg)**	**$\lambda_{0.5}$ (nm)**
TEPT5700	75	± 50	440 to 800

Note

- Test condition see table "Basic Characteristics"

ORDERING INFORMATION			
ORDERING CODE	**PACKAGING**	**REMARKS**	**PACKAGE FORM**
TEPT5700	Bulk	MOQ: 4000 pcs, 4000 pcs/bulk. Label with I_{PCE} group on each bulk. Specifications of group A/B/C see table "Type Dedicated Characteristics" on page 2	T-1¾

Note

- MOQ: minimum order quantity

ABSOLUTE MAXIMUM RATINGS (T_{amb} = 25 °C, unless otherwise specified)				
PARAMETER	**TEST CONDITION**	**SYMBOL**	**VALUE**	**UNIT**
Collector emitter voltage		V_{CEO}	6	V
Emitter collector voltage		V_{ECO}	1.5	V
Collector current		I_C	20	mA
Power dissipation	$T_{amb} \leq 55$ °C	P_V	100	mW
Junction temperature		T_j	100	°C
Operating temperature range		T_{amb}	- 40 to + 85	°C
Storage temperature range		T_{stg}	- 40 to + 100	°C
Soldering temperature	t ≤ 5 s, 2 mm distance to package	T_{sd}	260	°C
Thermal resistance junction/ambient	J-STD-051, soldered on PCB	R_{thJA}	230	K/W

For technical questions, contact: detectortechsupport@vishay.com

Ambient Light Sensor

20118

DESCRIPTION

TEPT5700 ambient light sensor is a silicon NPN epitaxial planar phototransistor in a T-1¾ package. It is sensitive to visible light much like the human eye and has peak sensitivity at 570 nm.

FEATURES

- Package type: leaded
- Package form: T-1¾
- Dimensions (in mm): Ø 5
- High photo sensitivity
- Adapted to human eye responsivity
- Angle of half sensitivity: φ = ± 50°
- Compliant to RoHS Directive 2002/95/EC and in accordance to WEEE 2002/96/EC

Pb Pb-free
e4
RoHS COMPLIANT
GREEN (5-2008)**

Note
** Please see document "Vishay Material Category Policy": www.vishay.com/doc?99902

APPLICATIONS

- Ambient light sensor for control of display backlight dimming in LCD displays and keypad backlighting of mobile devices and in industrial on/off-lighting operation

PRODUCT SUMMARY			
COMPONENT	**I_{PCE} (mA)**	**φ (deg)**	**$\lambda_{0.5}$ (nm)**
TEPT5700	75	± 50	440 to 800

Note
- Test condition see table "Basic Characteristics"

ORDERING INFORMATION			
ORDERING CODE	**PACKAGING**	**REMARKS**	**PACKAGE FORM**
TEPT5700	Bulk	MOQ: 4000 pcs, 4000 pcs/bulk. Label with I_{PCE} group on each bulk. Specifications of group A/B/C see table "Type Dedicated Characteristics" on page 2	T-1¾

Note
- MOQ: minimum order quantity

ABSOLUTE MAXIMUM RATINGS (T_{amb} = 25 °C, unless otherwise specified)				
PARAMETER	**TEST CONDITION**	**SYMBOL**	**VALUE**	**UNIT**
Collector emitter voltage		V_{CEO}	6	V
Emitter collector voltage		V_{ECO}	1.5	V
Collector current		I_C	20	mA
Power dissipation	$T_{amb} \leq 55$ °C	P_V	100	mW
Junction temperature		T_j	100	°C
Operating temperature range		T_{amb}	- 40 to + 85	°C
Storage temperature range		T_{stg}	- 40 to + 100	°C
Soldering temperature	t ≤ 5 s, 2 mm distance to package	T_{sd}	260	°C
Thermal resistance junction/ambient	J-STD-051, soldered on PCB	R_{thJA}	230	K/W

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