EE 40 Final Project – Basic Circuit

Part I: General instruction

1. The final project will count 30% of the lab grading, since it's going to take 3 lab sessions. All other individual labs will count 70% of the lab grading; each of them counts 10%.
2. This project is composed of a basic part and a creation part. A circuit diagram will be provided for the basic part, which is required to be finished at the end of the semester. There are four creation questions with different complexity and different bonus credits. No circuit diagrams will be provided for the creation part. You have to design the circuit to realize the function by your own using the components that we can supply. You are allowed to discuss with other students and your GSIs. GSIs can help you analyze if the circuit works but we won't give any hints on the design for the first three questions. For the last open question, you are welcome to do whatever you think will be worth doing using the components we have, and discuss any possible function design with your GSIs. (We may still make modifications to the "freeform/creative" portion at the end of the lab, so for the first week just focus on building the basic circuit diagram and doing analysis for your report)
3. Every effort must be made to team up as a team of 2, and if necessary you can change session; only under special circumstances and approval by head GSI is required for forming a team of 3 or doing it alone. One of your team members will keep the board and the components during the project period. Try to protect your progress, and keep it in a good condition.
4. Every group will get a project kit with a piece of breadboard and all the components. Please check with the component list in lab guide part V to see if the kit is complete. Keep it in a good condition during the whole project. We don't have many extra parts to supply if you lose any of them.
5. The grading will be mainly based on the lab report and the circuit functionality. A typed lab report is preferred. Hand written is also fine, but has to be neat and clear. Please see part IV for more information on the lab report.

Part II: Basic Circuit—Light Sensor

1. Function analysis

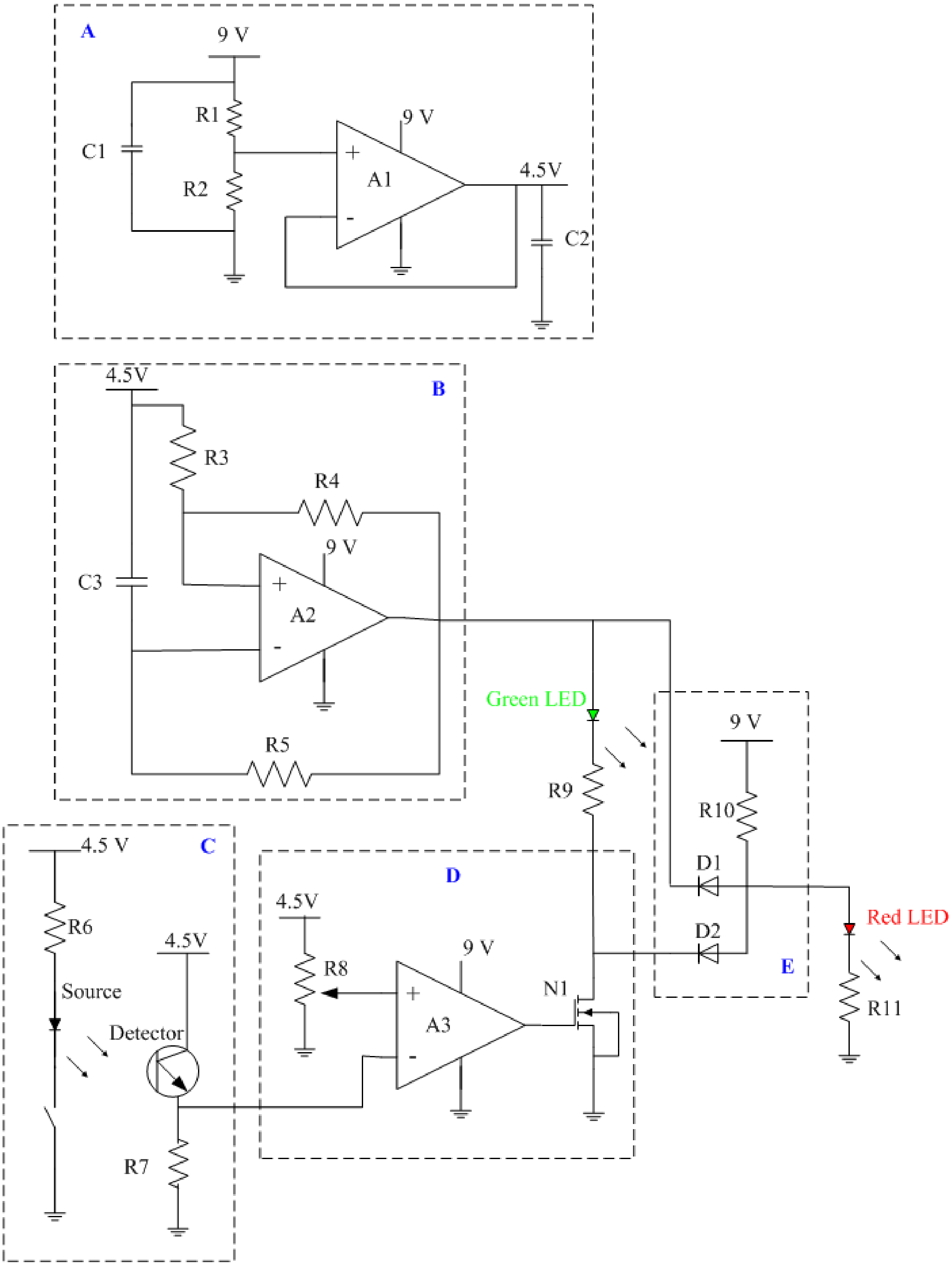


Figure 1. Basic circuit diagram

This is a light (visible or infrared) sensing circuit. When there is no light shinning on the detector in the circuit (the circuit element you use for visible or IR light detection), the green LED will be flashing. When there is no light shining on the detector, the red LED will start flashing instead of the green one.
The whole circuit can be broken down into 5 basic building blocks labeled A-E in the diagram. We will analyze them one by one in order to understand the functions.

A. 4.5 V DC power supply.

The circuit is going to be powered by a 9 V battery, but lower DC power is also needed in the circuit. Part A is using an op-amp to build up a simple voltage follower which gives 4.5 V output. Since 4.5 V is half of 9 V, resistors R1 and R2 are equal. C1 and C2 are filtering capacitors, which are usually connected in parallel with the DC output in order to filter out any high frequency AC signal coming from the noise.

B. Square wave oscillator.

Let's analyze it in a time sequence and use 4.5 V as the voltage reference. The circuit diagram can be redrawn as shown in Figure 2 (b).

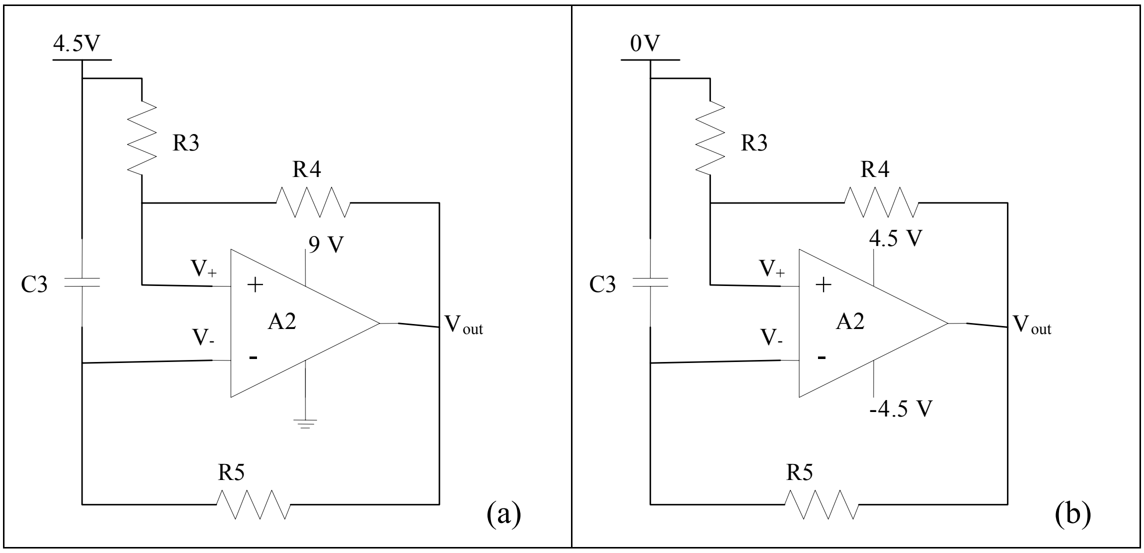


Figure 2. Square wave oscillator (a) with reference at 0 V. (b) with reference at 4.5 V.

Initially $V_{out} = 0$ and there is no charge on the capacitor. However to the reference 4.5 V, $V_{out} = -4.5\,\text{V}$ and $V_{-} = -4.5\,\text{V}$. Since this circuit has a positive feedback loop, any slight difference between V+ and V- may make V_{out} high or low clamped to the power supply value. In this initial condition,

$V_+ = -4.5\frac{R_3}{R_3+R_4} > V_-$ *and* $V_- = -4.5\,\text{V}$, so the output goes high and get clamped to 4.5 V immediately after the circuit is on. Now the circuit is in state 1: $V_{out} = 4.5\,\text{V}$, $V_+ = 4.5\frac{R_3}{R_3+R_4}$ and capacitor C3 is being charged from V_{out}. So V- is rising up. When V- is as high as or just slightly higher than V+, the circuit toggles because of the positive feedback. So after the capacitor charges to a voltage higher than V_+, Output will then be clamped at -4.5 V since $V_- > V_+$. Now the circuit is in state 2: $V_{out} = -4.5\,\text{V}$ and $V_+ = -4.5\frac{R_3}{R_3+R_4}$. The capacitor is being discharged from V_{out}. And V- is falling down. When V- is as low as V+ or just slightly lower than V+, the circuit toggles again because of the positive feedback. Then the output is clamped at 4.5 V again, $V_+ = 4.5\frac{R_3}{R_3+R_4}$ and the capacitor is being charged from V_{out} again.

Therefore, we see that the circuit is toggling between the two states, and the output voltage is either 4.5 V or -4.5 V, which forms a periodic square wave. To understand the oscillation function better, we draw wave forms at V_+, V_- and V_{out} on the same scale as shown in Figure 3(b). It's clear that the threshold voltages of output high and low are $4.5\times\frac{R_3}{R_3+R_4}$ V and $-4.5\times\frac{R_3}{R_3+R_4}$ V. Go back to the original circuit with reference at 0 V. We just need to add a DC offset 4.5 V to all the result and waveforms as shown in Figure 3 (a). The threshold voltages changes to $4.5\frac{2R_3+R_4}{R_3+R_4}$ and $4.5\frac{R_4}{R_3+R_4}$.

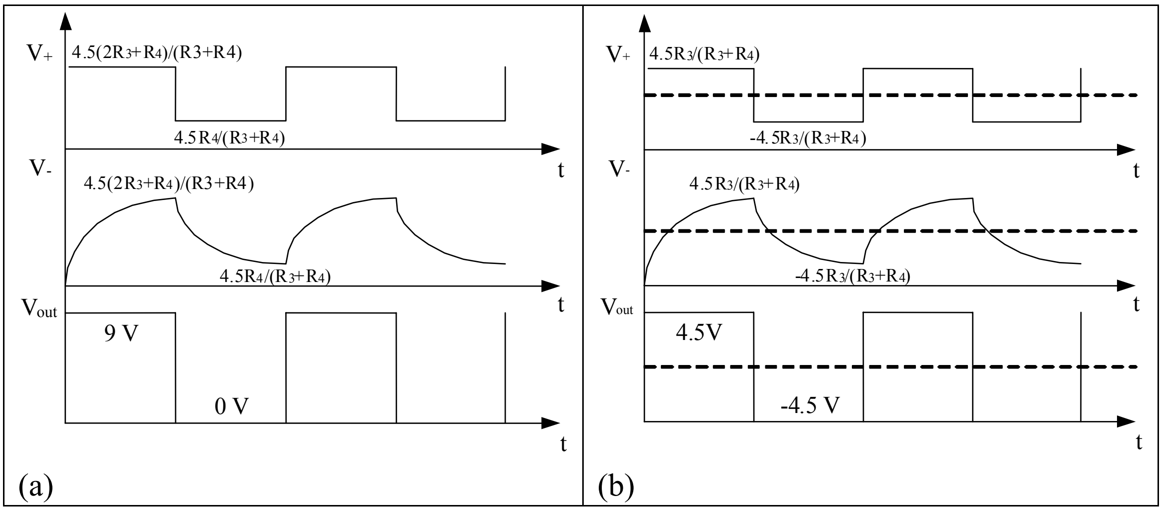
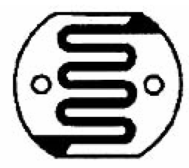


Figure 3. Waveforms of V_+, V_- and V_{out} (a) with reference of 0 V. (b) with reference of 4.5 V

C. Light generation and detection.

Visible Light (room light), For Basic Circuit

This basic circuit can be made to detect either visible or infrared light. When you first build the circuit, you should start with the photoresistor – the thin disk shaped element with two pins and squiggly lines on top. This is the easiest to implement since you don't need to wire up a light source (and easier to debug since you can see visible light!). The photoresistor simply changes its resistance based on how much light is hitting it. The exact range may vary, but you might expect something like 1kohm when light hits it, and 10k or above when it is in the dark. The photoresistor is made of a semiconductor (such as cadmium sulfide), and when light hits it, electrons jump from the valence to conduction band where they can move around, and so the conductivity increases.



Drawing of photoresistor

Infrared Light (try this when the rest of the circuit is all complete)

In at the end of the lab after you've finished , we will ask you to replace the photoresistor with the infrared source and detector and report on that setup as well (both in section C of the report). The transparent blueish LED is your infrared (IR) light source. Section 2 gives suggestions for optimal resistor values to use for the IR source. The black LED-like circuit elements are the IR phototransistors. (The black plastic covering them blocks visible light, but passes IR frequencies). They only have their source and drain pins sticking out. When light hits the detector, it has the effect of raising the voltage of the transistor base terminal inside the package, and so conductivity increases between the source and drain terminals. Further description and recommended resistor values are in section 2.

Strong Visible Light Source

There is also a visible phototransistor available for you to use for less sensitive light detection in the creative/bonus part of the lab. This requires a flashlight or

other intense light to activate. Further description is in section 2.

D. Comparator and buffer.

The open loop op-amp can be used as a comparator. The positive input connects to a fixed DC voltage used as a reference voltage. Negative input connects to the detector end. When detector detects light, current increases through the detector (whether you're using the photoresistor or phototransistors, the effect is basically the same). Therefore the voltage across R7, which is connected to the negative input of the op-amp, increases. When it's lower than the reference voltage, the output of the comparator will be high—9 V. When it's higher than the reference, the output is low—0 V. Thus the light on/off is converted to L/H of the op-amp output. An NMOS will be connected to the output of the comparator as a buffer since the output will be driving the LED and the logic circuit following. When comparator output (gate voltage of the NMOS) is low, the NMOS is off, thus the drain is high or floating. When comparator output is high, the NMOS is on, thus the drain is grounded. This way, we realize the light on/off to output H/L conversion.

E. AND gate.

Only when both inputs are high, the output is high, which will light up the red LED. Both inputs will be high when the light is on (and the NMOS turns off) and when the "blinking" oscillator is also high. Hence, using the AND gate, you pass the ~1-30Hz blinking signal from the green LED to the red LED, and since the comparator turned off the NMOS, the green LED cannot light up.

Based on the functions of all the building blocks, the function of the whole circuit is as follows. When light is off, the comparator buffer output is low. So the AND output is low, thus red LED is off. However, the oscillator output will make the green LED flashing. When the light is on, the comparator buffer output is high (9 V), so the AND gate output is high when the oscillator output is in the high period, thus the square wave signal is transmitted to the red LED, which will be flashing then. In addition, because of LED is a diode, which can only work in one direction, the green LED is off when comparator buffer output is high.

2. Hands-on – building the circuit

To build and debug each block separately and then combine them together to realize the whole function will make the process faster and easier. Try to make your circuit clear, compact and neat. Keep your wires short! It will be nice-looking and most importantly easy to debug. It will also make the lab report much easier since you can break each block down.

We will give general considerations of how to select values of the components and

provide recommended values and specifications for some parts.

A. Op-amp is LMC 6482, the same as we used in Lab 6. Power supply will be from a 9 V battery. So V+ (pin 8) is 9 V and V- (pin 4) is 0 V or ground of the circuit. Since the output is 4.5 V, half of the power, we need two equal resistors for R1 and R2. To make the power consumption low, we use 10kΩ for R1 and R2. Filter capacitors C1 and C2 can be 10µF. Smaller values can be used if high frequency noise exists. BE CAREFUL OF THE POLARITY OF THE CAPACITORS, when connecting them to DC voltage. Remember, the longer pin is the + terminal of the capacitor and ideally voltage across it should be biased accordingly.

B. Human eyes can differentiate frequencies smaller than 30 Hz. So we need to make the oscillator frequency in the range 1 ~ 30 Hz. In order to express the frequency in terms of R3, R4 and R5 and C3, let's do some calculations based on the analysis in the above section. Since the two threshold values are symmetric as shown in Figure 3, we know that the duty cycle of the square wave is 50% (half period 9 V and half period 0 V). The period of the square wave is decided by the capacitor charging time constant R5×C3. Let's use the rising half period of V- in Figure 3(a). Since this is a first order RC circuit, the rising part can be express as:

$V_- = 9\left(1 - e^{-\frac{t}{R_5 C_3}}\right)$. At time t_1, $V_- = 9\left(1 - e^{-\frac{t_1}{R_5 C_3}}\right) = 4.5\frac{R_4}{R_3 + R_4}$; at time t_2, $V_- = 9\left(1 - e^{-\frac{t_2}{R_5 C_3}}\right) = 4.5\frac{2R_3 + R_4}{R_3 + R_4}$. The time period $t_2 - t_1 = \frac{T}{2}$, where T is the period of the square wave. So

$$\frac{T}{2} = t_2 - t_1 = R_5 C_3 \ln\frac{2(R_3 + R_4)}{R_4} - R_5 C_3 \ln\frac{2(R_3 + R_4)}{2R_3 + R_4} = R_5 C_3 \ln\frac{2R_3 + R_4}{R_4}.$$

So the period is $T = 2R_5 C_3 \ln\frac{2R_3 + R_4}{R_4}$, and the frequency is

$f = \frac{1}{T} = \frac{1}{2R_5 C_3 \ln\frac{2R_3 + R_4}{R_4}}$. The falling half period of V- will give the same solution of the period or frequency since the signal is symmetric. So to control the frequency in the range of 1~30 Hz, we use R3=R5=10 kΩ, R4=510 Ω and C3=10 µF. Plug all these numbers in the frequency equation, we have the frequency of 1.35 Hz, which is detectable by human eyes.

C. For the light generation, if room light or flash light is being used; there is no need for light generation circuit. If an infrared (IR) LED is being used as an IR light

source; the maximum current is around 30 mA, and threshold voltage is about 1.7 V. So we use R6 = 200 Ω or similar to keep the current below 30 mA.

For the detection part, we use different R7 values for different detectors. If the visible light phototransistor is being used, which can detect intense white light (so a flash light has to be the source), R7 can be 10 kΩ to keep the current smaller than the maximum 25 mA and also keep the power consumption low.

If photoresistor is being used, which can detect low intensity light, or just general room light, R7 = 1 kΩ would be a good choice. When room light is on, the resistance will be less than 1kΩ (results may vary, check yourself to see). With room light off or simply blocking the surface of it, the resistance will be greater than 10kΩ (also check this yourself to find the actual value). So R7 and the photoresistor form a simple voltage divider. So $V_+ = \frac{R_7}{R_7 + R_{\text{detector}}} \times 4.5\text{ V}$. Table 1 gives a summary of components, values as well as output voltage ranges of different source/detector schemes.

Source/Detector	**R6 (Ω)**	**R7 (Ω)**	**Output /V-(V)**
Flash light / phototransistor	-	10 k	0~4
Room light / photoresistor **(for basic circuit)**	-	1 k	2~4
IR LED / IR detector	200	10 k	0~4

Table 1. Light source and detector schemes

D. Pot R8 is a voltage divider too. You can think of the potentiometer as being a 10kΩ resistor where you can "tap in" somewhere along the resistor, so you end up getting a circuit that looks just like a voltage divider where R1+R2=10kΩ. So this potentiometer needs to be tuned to the value that makes the output voltage of the potentiometer's middle pin roughly in the middle of the on-off range of V- in order to distinguish light-on and light-off states. A 10kΩ pot will be used to provide the voltage reference. Turn it until the output voltage is about 2.5-3 V or even higher, depending on which detector is being used. You can pick the right voltage for this comparator by measuring the voltage output of your detector circuit (on the V_- terminal) with your source on and off. After you've picked a value, you can play with the pot setting to get the desired sensitivity.

The NMOS is BS170. The gate threshold voltage is about 2.2 V. Please refer to the spec for more information. (The pin diagram is weird looking – the middle pin is

actually the base, even though the pins are at an angle in the drawing. Ask your TA if you're not sure).

E. D1and D2 can be 1N4148. To keep the current smaller than 30 mA for all the diodes (D1, D2 and LEDs), we use R9 = 1kΩ, R10 = R11 = 510Ω. Any other similar values will be fine too.

Table 2 summarizes all the components you may need to build the basic circuit.

R1	10 kΩ	**C1**	10 μF
R2	10 kΩ	**C2**	10 μF
R3	10 kΩ	**C3**	10 μF
R4	510 Ω	**D1/D2**	1N4148
R5	10 kΩ	**N1**	BS170
R6	-/-/ 200 Ω	**Op-amp**	LMC 6482
R7	10kΩ/1 kΩ/10 kΩ	**Light source**	Flash / Room / IR LED
R8	10 kΩ pot	**Detector**	phototransistor/ photoresistor/ IR detector
R9	1 kΩ		
R10	510 Ω	**Battery**	9 V
R11	510 Ω	**LEDs**	Green and Red

Table 2. Basic circuit components summary

Part V: Component list

Component	Value	Quantity
Resistor	10 kΩ	8
	1 kΩ	3
	510 Ω	3
	200 Ω	1
Pot (3 pins, large black dial)	10 kΩ	3
Capacitor	10 µF	3
	0.1 µF	1 (very tiny!)

Component	Model	Quantity
Op-amp IC	LMC 6482	2 (maybe 1 additional)
NMOS (see datasheet, has bent pin for base)	BS170	3
PMOS (see data sheet, all straight pins)	ZVP2106A	1
Diode	1N4148	2
Visible LED (longer pin is + side)	Green, Yellow, Red	3
IR LED (clear blue-ish color)	-	1
IR detector (black cover, looks like an LED)	-	1
Phototransistor (clear, looks like LED)	-	1
Photoresistor (small disk with squiggly lines)	-	1
Buzzer (large black speaker)	-	1
Microphone (erase-sized	-	1

piece with two wire leads		
Battery	**9 V**	**1**
Breadboard	**-**	**1**