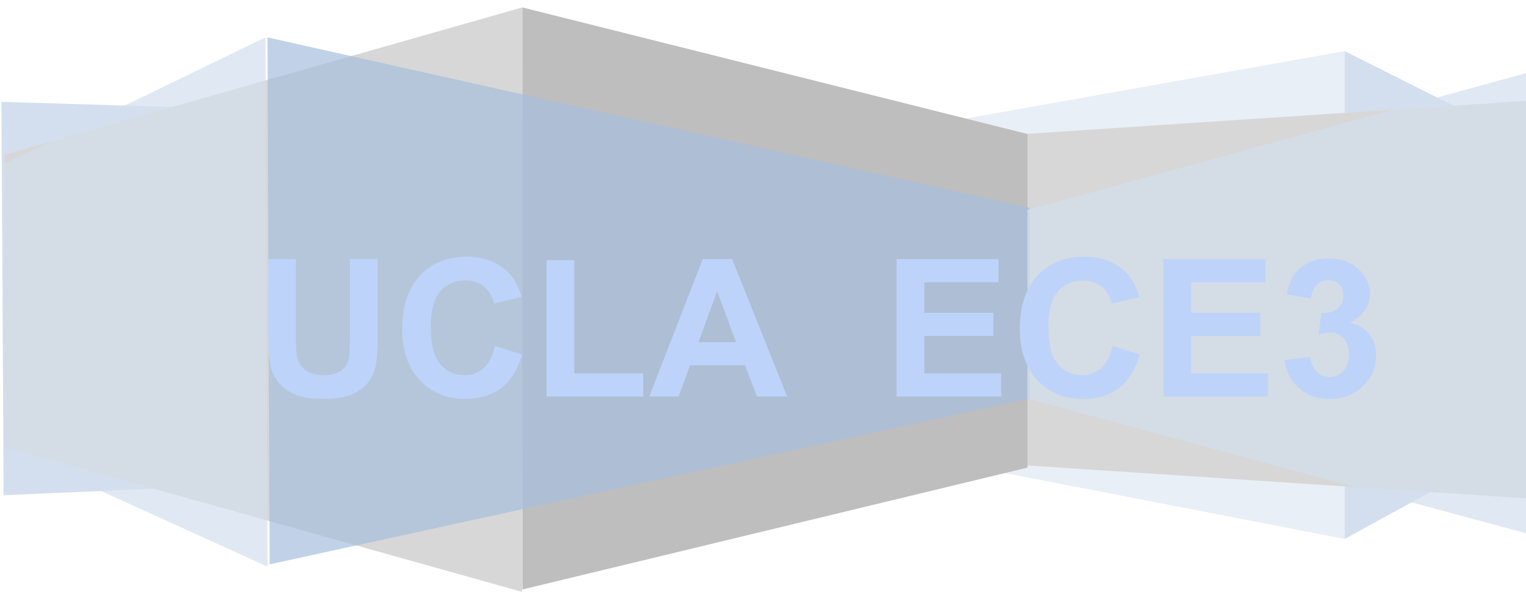
EE3 Introduction to Electrical Engineering

LABORATORY MANUAL



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Department of Electrical Engineering
October 2013
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Rev. October 2019 (version 1.10; Dr. Dennis M. Briggs)
Rev. September 2020 (version 1.11; Dr. Dennis M. Briggs)

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Previous students of EE3 gave us many suggestions that we have attempted to include in the re-design of this important "Introduction to Electrical Engineering."

Finally, I thank the Elenco Corporation for the generous use of their copyrighted materials.

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Student Albert Liu contributed much to Version 1.9, both in providing constructive ideas and in seeing that the changes were implemented.

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-Dr. Michael Briggs, 2020

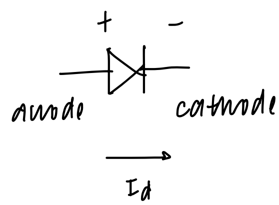
TA Dhruv Srinivas has contributed to the Lab 3 portion of the Lab Manual.

Week 3: LEDs, Phototransistors and Motor Control

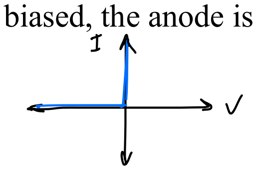
It is *HIGHLY RECOMMENDED* that you read through this week's lab and familiarize yourself with all the material before attending the lab session—there is a lot of content in this week's lab and all these materials are closely related to the underlying control and sensing mechanism of your line-following robot project starting from the next lab!

Week 3 Prelab

1. Draw the circuit schematic symbol of a diode and label the anode and cathode.



2. When a diode is forward biased, the anode is at a (circle one) higher / lower voltage than the cathode.



3. When looking at the diode itself, what are the two methods for telling which side of an LED is the anode and which side is the cathode?

   side view: anode is longer leg. cathode is shorter leg

   top view: anode (rounded side), cathode (flat side)

4. Fill in the blank: When a __high__ voltage relative to the __emitter__ is applied to the __base__ of an NPN transistor, current is allowed to flow from the __collector__ to the __emitter__.

5. What is the unit of the RC time constant (in SI unit)? Why? <u>Show your reasoning below</u>:

   $R(\Omega) \quad C(F) \Rightarrow RC = \Omega F = \frac{\cancel{kg}\cdot\cancel{m^2}}{\cancel{A^2}\cdot\cancel{s^3}} \cdot \frac{\cancel{s^4}\cdot\cancel{A^2}}{\cancel{m^2}\cdot\cancel{kg}} = s$

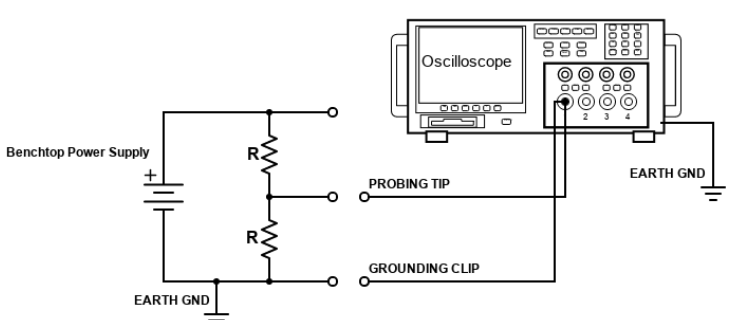
   $RC = s$

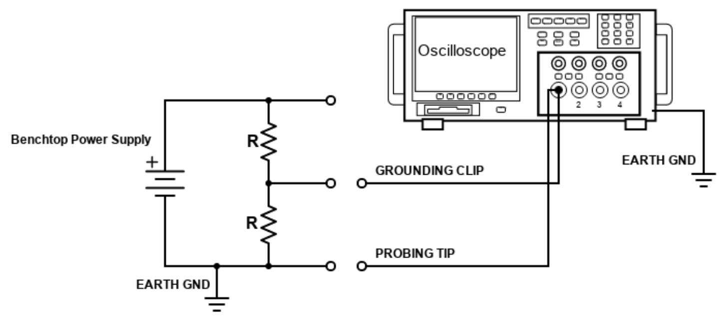
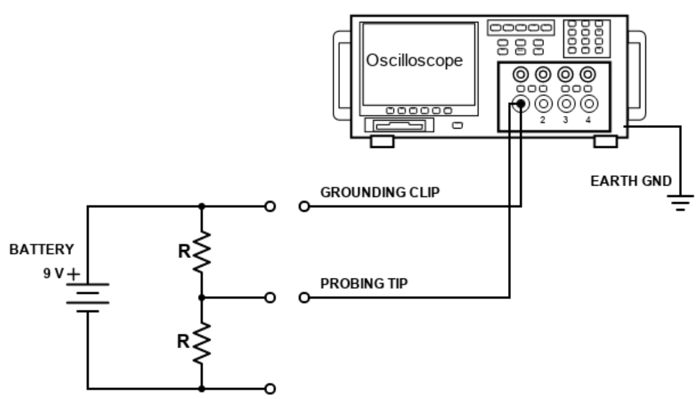
6. Single ended vs Differential Probing: If you were to use an oscilloscope in lab, the most common probe type you will use is the single ended probe as pictured:

https://www.newark.com/keysight-technologies/10073d/passive-probe-oscilloscope/dp/83R9177

Figure P3-1: Single Ended Probe

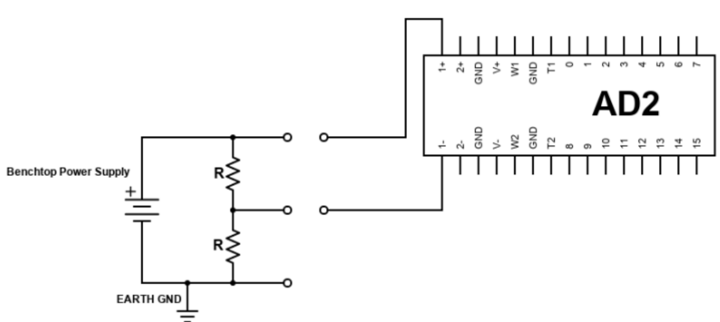
In this image, the probing tip is what you'd attach to the node whose voltage you want to measure in reference to the oscilloscope's ground. The grounding clip is indeed what the name suggests; it is a connection to the oscilloscope's ground which is also a connection to earth ground (since the oscilloscope is powered by mains)! **Please understand the importance of this distinction**. To illustrate, if you have a circuit that is powered by mains and you wish to probe it, attaching the grounding clip to the wrong point will create a short. This will likely result in damage to you, the circuit, and your oscilloscope! For this reason, when you are measuring a circuit powered by mains, you must attach the probe's grounding clip to the ground of the circuit (AND NO OTHER PLACE). With this knowledge, determine if the following circuits have the oscilloscope connected in a safe manner:

Circuits	Correct? (Yes or No)
	yes.

<table>
<tr><td>
</td><td>no.</td></tr>
<tr><td>
</td><td>no.

(NOTE THE CIRCUIT'S VOLTAGE SOURCE)</td></tr>
</table>

When using the AD2, you will find that the input channels are labeled 1+,1- and 2+,2- with no mention of ground. This is because the AD2 uses *differential probing*, not single ended probing. This means the AD2 measures a voltage at the (+) terminal and compares it to the voltage at the (–) terminal to get a voltage measurement. So here, ground is completely separate from the (–) terminal. With this knowledge, determine if the following circuits are connected in a safe manner:

<table>
<tr><td>Circuits</td><td>Correct? (Yes or No)</td></tr>
<tr><td>
</td><td>yes.</td></tr>
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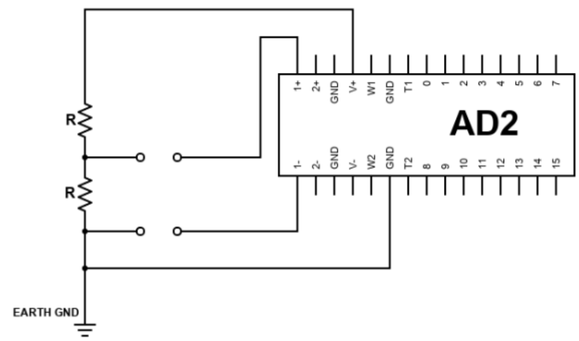
	yes.

Note: A DMM uses differential probing as well. This makes sense since DMMs are often handheld, battery powered devices so they cannot have a connection to earth ground.

Week 3 Prelab End

Overview of the Experiments

In today's lab we will be learning the basic operation principles of light-emitting diodes (LEDs) and phototransistors. Along with DC motors—which we will cover next week—these serve as important building blocks for the line-following robot project. Our class project, the line-following robot car can be understood, on a qualitative level, as a closed-loop feedback system as shown in the figure below:

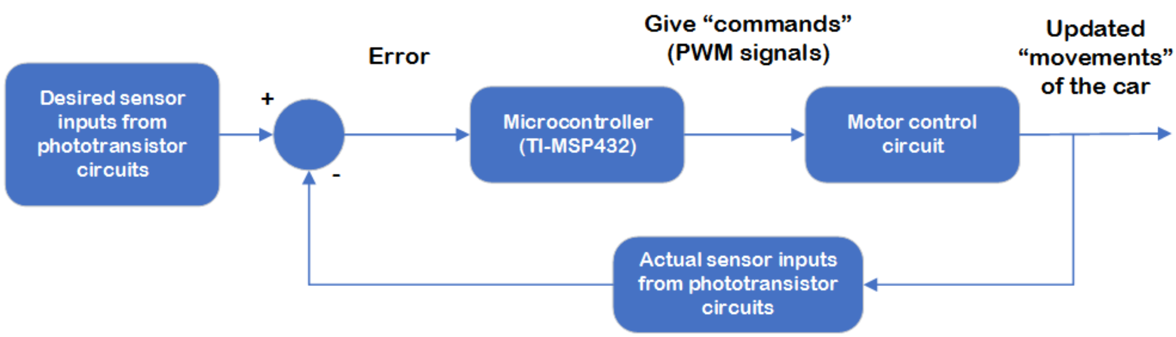


FIGURE 3-1: High level understanding of the ECE3 class project

As you can see from Figure 3-1, the general idea of our class project is to have the central processing microcontroller (TI-MSP432 board) of the line-following robot "efficiently" **adjust** the **output speed of its wheels (DC gear motors)**, according to the real-time changes in the sensory **input** collected from **the IR LED/phototransistor array**. Today, we will be investigating the operating principles of the key individual components in the line-following cars regarding their inputs (and outputs next week). In other words, we will be looking into how the line-following robots **transduce input light intensity information into electrical readouts (i.e., voltages or RC measurement times)**.

Before we start looking into the LED/phototransistor circuits, we'll start with some discussions and experimentations on the characteristics of LEDs and phototransistors.

Light-Emitting Diodes (LEDs)

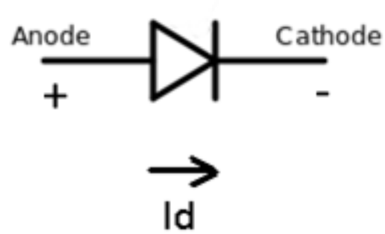


FIGURE 3-2: Diode Symbol

Diodes, also known as p-n junctions, are devices that do not follow Ohm's Law. Diodes have a non-linear relationship between current and voltage. Diodes are typically represented in diagrams by the symbol shown in Figure 3-2. The anode is also called the "positive side" and the cathode the "negative side". We first define I_d, the current flowing through the diode, as flowing from the anode to the cathode. In Figure 3-4, the diode is forward biased—that is, the anode is at a higher voltage than the cathode. We can see that under forward bias, the current-voltage relationship is exponential. In Figure 3-3, the diode is reverse biased, with the cathode at a higher voltage than the anode. The diode allows negligible current to pass under reverse bias.

A reasonably accurate mathematical model of the current-voltage relationship is:

$$I_d = I_0 (e^{V/V_t} - 1),$$

where V_t is known as the thermal voltage and is typically around 0.026 Volts and I_0 is known as the saturation current. The saturation current is typically only a fraction of a microampere.

Under reverse bias, $V \le -V_t$:

$$I_d \approx -I_0$$

As shown in Figure 3-3, this leads to a constant current (typically negligible and less than one microampere) in the reverse direction under reverse bias.

Under forward bias, i.e. $V \ge V_t$:

$$I_d \approx I_0 e^{V/V_t}$$

As shown in Figure 3-4, this leads to an exponential I-V curve under forward bias. Keep in mind that the slope of a device's I-V curve is indicative of its resistance. In fact, the reciprocal of the slope at a given point is its resistance at that point! Note that at low forward bias voltages, the slope is small, so the diode is operating in a region of high resistance. In contrast, at high forward bias voltages, the slope is large, so the diode is operating in region of low resistance. A forward-biased diode's transition from its high resistance region to its low resistance region occurs around 0.5~0.7 Volts and is known as a diode's turn-on voltage.

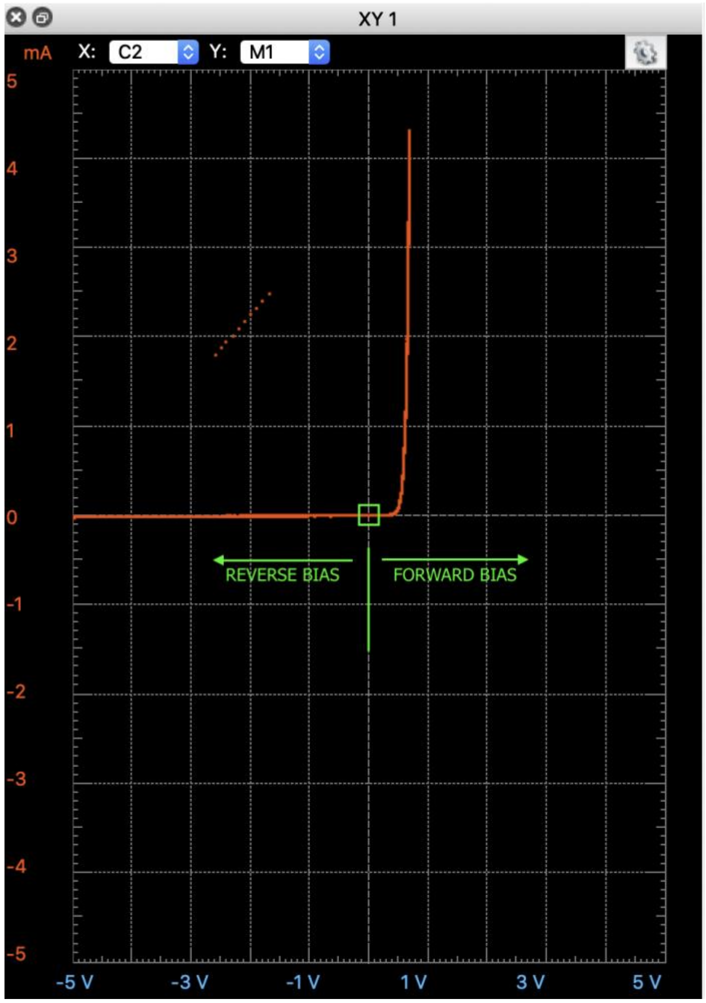


FIGURE 3-3: 1N4149 Diode Forward & Reverse Bias Characteristic (on the AD2)

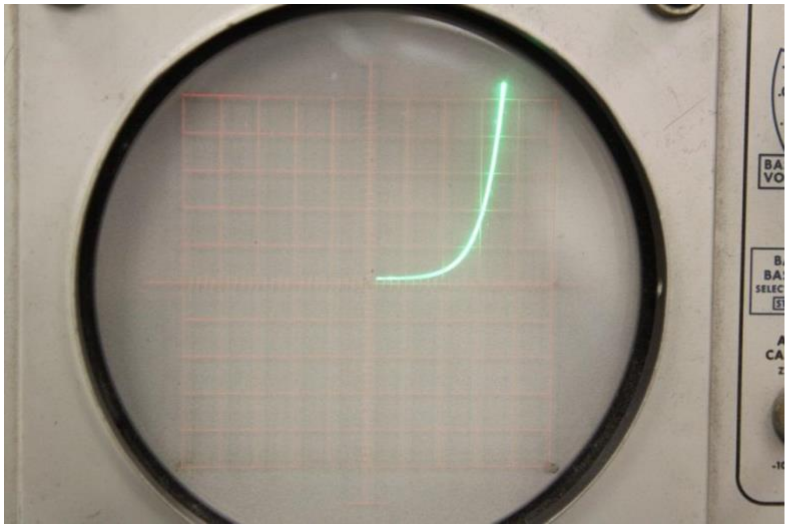


FIGURE 3-4: Diode Forward Bias Characteristic (on the old Transistor Curve Tracer)

Under forward bias, the typical voltage is in the order of a fraction of a volt for silicon devices.

To observe the characteristics of diodes, we will be experimenting with light-emitting diodes, also known as LEDs. When a large enough current passes through an LED in the forward direction, the LED will generate light.

There are two ways to tell which side of the LED is the anode and which is the cathode. This is shown in Figure 3-5 below.

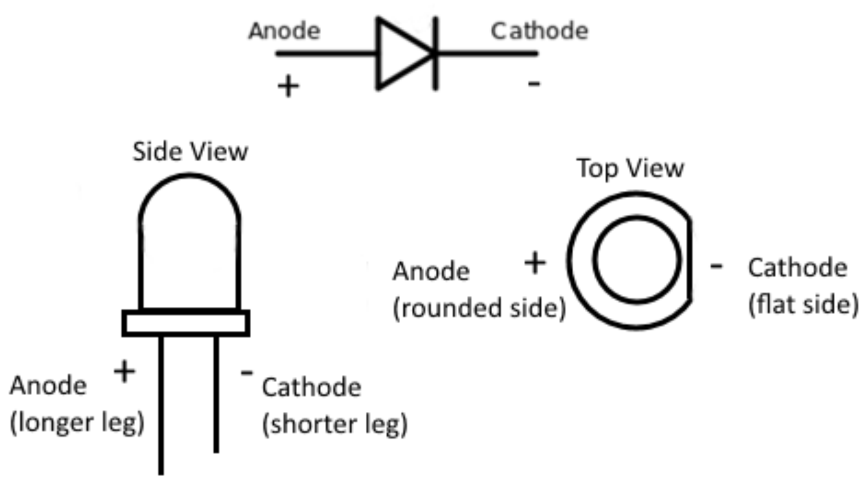


FIGURE 3-5: Physical Diode (VISIBLE LIGHT **ONLY**!)

NOTE: It is often times unreliable to determine polarity via leg length since component legs can be clipped or twisted. Also, in some IR LEDs, the shorter leg is the anode, but the flat is on the cathode side. Determining which sides are rounded and flat, or using the transistor curve tracer, is more reliable.

To test the current-voltage relationship of diodes, we will employ a **red visible-light** LED which can typically stand up to 30 milliamperes. Set up the circuit as below. **We will always need to keep a resistor in series with the LED, because not limiting the forward current may break it!**

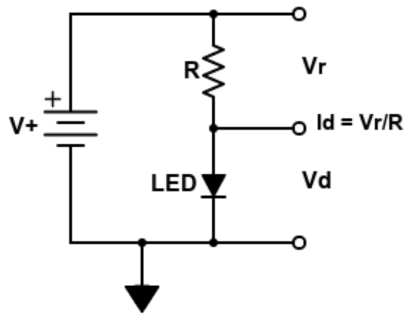


FIGURE 3-6: LED Experiment Setup[3]

The 0-5 volts AD2 **positive** voltage supply should be connected to the LED under test through a resistance of 220 ohms. We arrive at this value by using our LED current limit to get the minimum resistance 5 V / 25 mA = 200 ohms. When designing real circuits, we almost always adhere to using standard resistor values, therefore we round this up to 220 ohms.

Using the voltmeter, measure the voltage across the resistor (Vr) and the voltage across the LED (Vd) at given voltage supply values. As a suggestion, you can do this by measuring Vr on Channel 1 and Vd on Channel 2. Use split screen mode (from last week) to easily set and view the voltages.

This measurement allows one to find the current through the resistor via Ohm's Law. (Note: the potential across the 220-ohm resistor = 220 * I_{device}.) Because this is a series circuit, the current through the resistor is the same as that through the LED.

[3] NOTE: We can *directly* measure Vr here since the AD2 uses differential probing. Using a single ended probe, you would have to measure Vd and V+ to find (V+) – (Vd) = Vr.

WORK SHEET HERE:

Supply Voltage	$Voltage_{Resistor}$	$Voltage_{LED}$	$Current_{LED}$ ($V_{resistor}$ / 220)
0 V[4]	-2mV	10 mV	-9.1 mA
0.5 V	-4 mV	502mV	-18.2 mA
1.0 V	-4 mV	1.004 V	-18.2 mA
1.5 V	-2mV	1.496V	-9.1 mA
2.0 V	300 mV	1.696V	1.4 mA
2.5 V	742 mV	1.756V	3.4 mA
5.0 V	3.05V	1.934V	13.9 mA

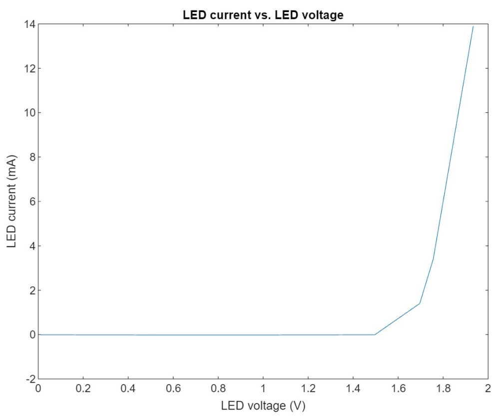
At approximately what LED voltage does the LED start to glow?

2V

[4] Turn the voltage supply off to achieve this. Note that you may see a non-zero reading on the voltmeter. The power supply has an absolute accuracy of ±10 mV and the voltmeter has an absolute accuracy of ±5 mV (for voltages < 0.5 V). Convince yourself whether or not this non-zero reading is unreasonable.

Using your favorite plotting app (Excel, Numbers, or Matlab; there are others), plot LED current (y-axis) vs. LED voltage (x-axis). Paste a screenshot of the plot in the given space below.

ANSWER HERE




```
>> x = [.01, .502, 1.004, 1.496, 1.696, 1.756, 1.934]

x =

    0.0100    0.5020    1.0040    1.4960    1.6960    1.7560    1.9340

>> y = [-.0091, -.0182, -.0182, -.0091, 1.4, 3.4, 13.9]

y =

   -0.0091   -0.0182   -0.0182   -0.0091    1.4000    3.4000   13.9000

>> plot(x, y), xlabel('LED voltage (V)'), ylabel('LED current (mA)'), title('LED current vs. LED voltage')
```

When choosing the resistor value for this circuit, we placed an upper bound on the diode current (25 mA) and used the max power supply voltage (5 V) to calculate a minimum resistance (5 V/25 mA = 200 ohm) to prevent damage to the LED. In the lab, you actually found that the diode current at a 5 V supply voltage was less than 25 mA! Explain why this is the case. (Note that this reduction in current is **not only** from rounding 200 ohms to 220 ohms)

ANSWER HERE

Diodes are not ideal when performing an experiment in real time. It will have a voltage drop based on its type or color of LED. This reduces the effective voltage in the circuit. Voltage is directly proportional to current, so a reduction in effective voltage means a reduction in the diode current.

Other factors may have contributed to a lower diode current, such as if the power supply voltage was lower than 5V or the actual resistance of the resistor was less than 220 Ohms because resistors have tolerance.

In circuit theory, we sometimes make the simplification that once a diode is forward biased or "on", the voltage across a diode does not change[5]. Using the Vd you measured at a 5 V supply voltage, calculate the resistor value to place the diode current at exactly 25 mA. Show your work:

[5] This is called the Constant-Voltage Drop model for a diode (covered in ECE 115A).

ANSWER HERE

$V_r = V_s - V_d = 5 - V_d$ $\quad$ $V_r = iR$

$iR = 5 - V_d$ $\quad$ $i = 25mA$

$$R = \frac{5 - V_d}{i} = \frac{5 - 1.934}{25mA} = 122.64\ \Omega$$

Phototransistors

In order to understand how phototransistors work, we will first look at a regular transistor. Transistors are three terminal devices that act as linear amplifiers, or, on a basic level, as switches. In this class, we will primarily be working with *Bipolar Junction Transistors*, or BJTs, shown in the figure below. BJTs have three terminals labeled base (B), collector (C), and emitter (E). The direction of the arrow points in the direction of current flow. (The symbol and operation listed in Figure 3-9 is for an NPN BJT. You may work with PNP BJTs later for your project, which have a different symbol and operation.)

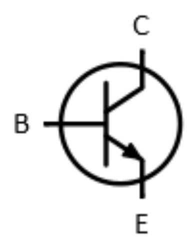


FIGURE 3-9: NPN BJT Symbol

In an NPN BJT, when a high voltage with respect to the emitter is applied to the base, current is allowed to flow from the collector to the emitter. When a low voltage with respect to the emitter is applied to the base, current is no longer allowed to flow from the collector to the emitter. This allows the transistor to act as an electrically controlled switch.

In this portion of the lab, we will work with BJT-based phototransistors. BJT-based phototransistors have an *exposed base* that is sensitive to light. When light shines on the base, the phototransistor allows current to flow from the collector to the emitter. **Within the scope of this course,** in general we can think of **phototransistors as variable resistors with its resistance depending on the incoming light intensity. The higher the incoming light intensity (brighter), the less effective resistance the phototransistors will have.**

In this course we will introduce one way of "reading" light intensity information from phototransistors. Namely, reading the change in the "RC measurement time". This is essentially the general strategy used for collecting inputs from the phototransistor array in your actual line-following car, and we will be qualitatively examining this strategy using discrete circuit components on a breadboard today.

Reading from Phototransistors – RC Charging/Discharging Time Based Measurement

Capacitances

Before discussing the exact phototransistor circuit, we will start by reviewing the notion of **capacitance** and the behavior of **1st order series connection RC circuits.**

Capacitance is the ratio of the change in an electric charge in a system to the corresponding change in its electric potential (voltage). It's defined as:

$$C = \frac{Q}{V} \quad \text{(Equation 1)}$$

Capacitance has a unit of Farad, for which 1 Farad = 1 Coulomb / 1 Volt.

Generally speaking in term of electrical circuits, we would prefer describing the behaviors of devices in term of currents and voltages. To introduce the variable of current into Equation 1, we use the fact that:

$$I = \frac{dQ}{dt} \quad \text{(Equation 2)}$$

Current is defined as the rate of change (w.r.t. time) of electric charge. Massaging Equations 1 and 2 we can arrive at the I-V relationship of a capacitor:

$$I_c = C\frac{dV_c}{dt} \quad \text{(Equation 3)}$$

Now let's take a look at a first order series connection RC circuit:

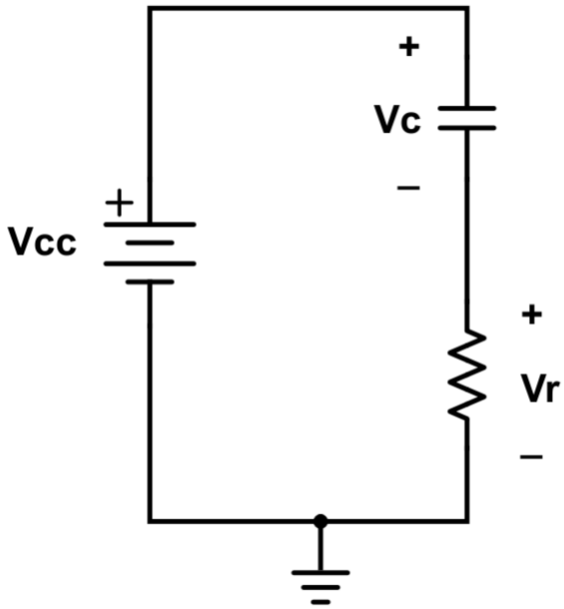


FIGURE 3-10: First Order Series Connection RC Circuit[6]

With the help of Equation 3, we can write down the KCL equation for this circuit:

$$I_c = I_r \;\rightarrow\; C\frac{dV_c}{dt} = \frac{V_r}{R} \;\rightarrow\; C\frac{dV_c}{dt} = \frac{V_{cc} - V_c}{R} \;\rightarrow\; \frac{dV_c}{dt} + \frac{V_c}{RC} = \frac{V_{cc}}{RC}$$

This is obviously a linear differential equation of order 1 (recall your differential equation course Math 33B). It can be solved using the integrating factor method, and the solution would be:

$$V_c e^{\int Pdx} = \int (Qe^{\int Pdx})dx + K, P = \frac{1}{RC}, Q = \frac{V_{cc}}{RC}$$

Which simplifies to:

$$V_c(t) = V_{cc} + Ke^{-\frac{t}{RC}} \quad \text{(Equation 4)}$$

$$V_r(t) = V_{cc} - V_c(t) = -Ke^{-\frac{t}{RC}} \quad \text{(Equation 5)}$$

[6] Vcc stands for Voltage Common Collector. For our purposes, this is equivalent to V+ on the AD2.

Where K is a constant determined by the **initial condition** on the capacitor $V_c(t = 0)$. If we assume there's no initial condition on the capacitor before t=0 (i.e., $V_c(0) = 0$). Then by plugging in this initial condition to Equation 4 we have:

$$V_c(0) = V_{cc} + Ke^{-\frac{0}{RC}} = V_{cc} + K = 0 \quad \rightarrow \quad K = -V_{cc}$$

Rewriting Equations 4 and 5 we have arrived at the equations for first order RC circuits with **no** initial condition:

$$V_c(t) = V_{cc} - V_{cc}e^{-\frac{t}{RC}} \quad \text{(Equation 6)}$$

$$V_r(t) = V_{cc} - V_c(t) = V_{cc}e^{-\frac{t}{RC}} \quad \text{(Equation 7)}$$

The **time-constant**, which is the product of the resistance R and the capacitance C, determines **how fast** V_c would settle to its **steady state value** $V_c(t \rightarrow \infty) = V_{cc}$. An observation we can make from Equation 4: the **smaller the RC time constant is, the faster that V_c would converge to its steady state value**. To visualize this behavior, we can choose $V_{cc} = 3.3V$ and $V_c(0) = 0$ for Equation 4 and 5, and plot the behavior of $V_c(t)$ and $V_r(t)$ with different RC time constant values:

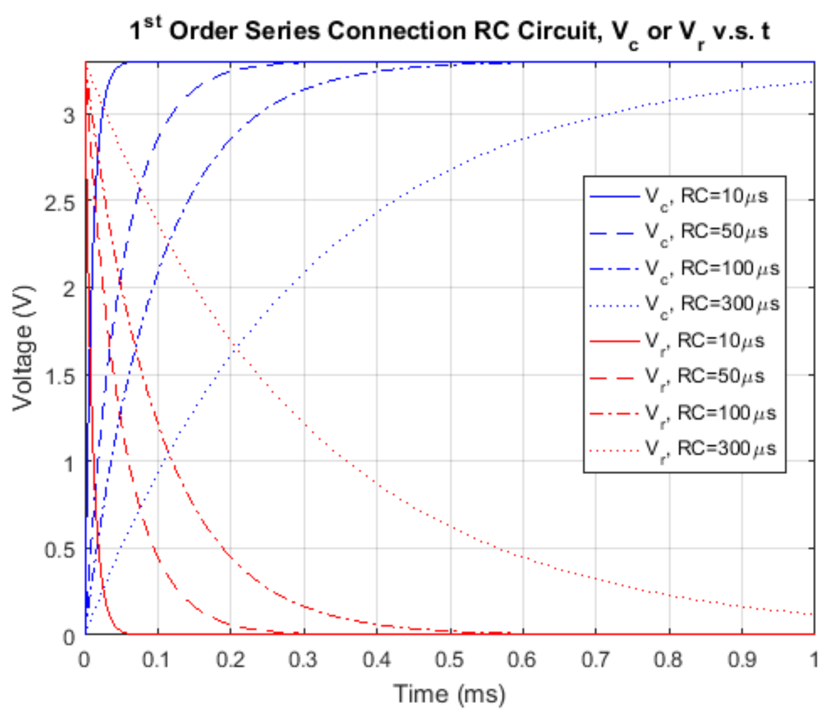


FIGURE 3-11: Voltage across capacitor/resistor over time with different RC time constants

From Figure 11 we can observe that after 5 time constants (5*RC), we can assume that all the changes have effectively died out and we reach the steady state. Five time constants is a good approximation of the *Settling Time*.

Related Phototransistor Circuit Experiment - Theory

The working principle of the phototransistor circuit on the actual line-following robot car can be qualitatively modelled as a two-stage process that can be understood as the following circuit diagram:

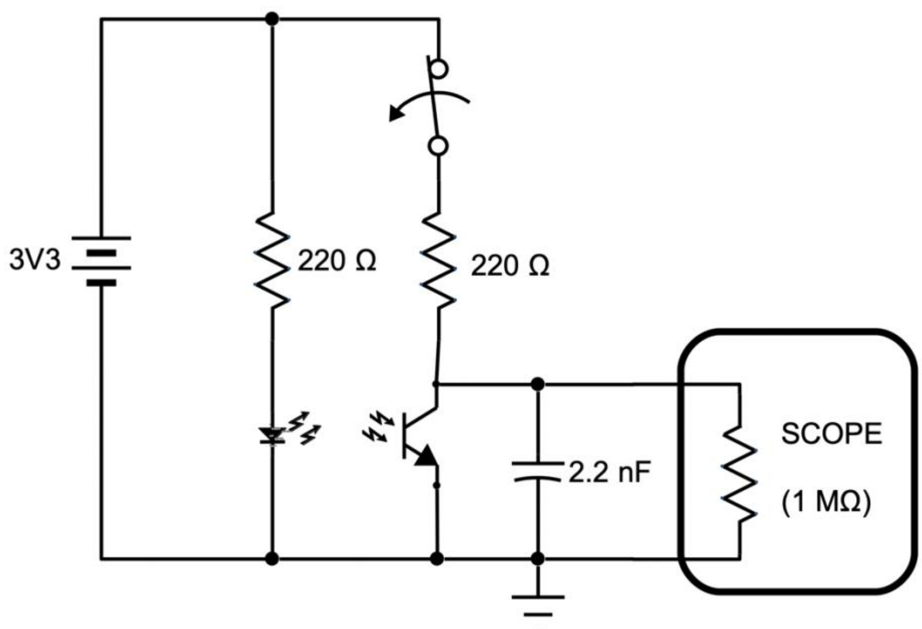


FIGURE 3-12: Simulation of phototransistor circuit (stage 1 and stage 2)

To ease the analysis of the above circuit, we can decompose the switching process in the above circuit diagram into individual equivalent circuits. The equivalent circuit of the first stage is shown in Figure 13 below:

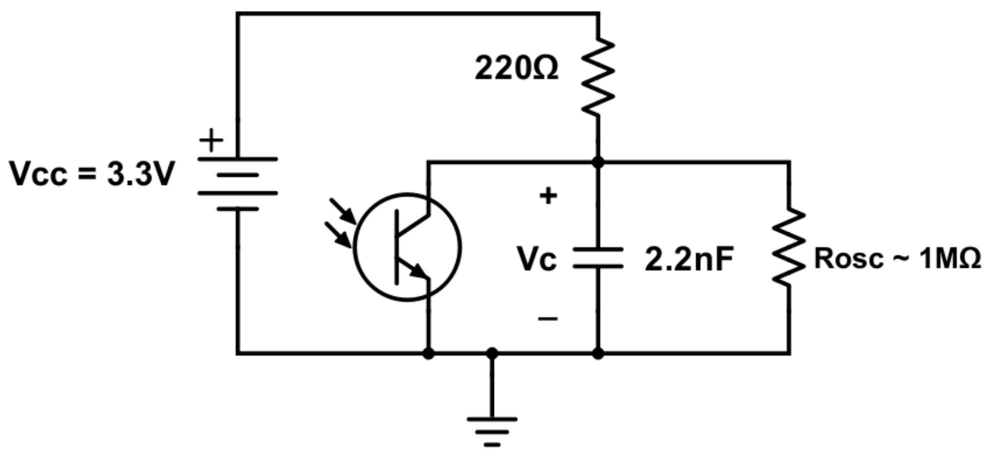


FIGURE 3-13: Simulation of the phototransistor circuit in our class project, stage 1

Note that the phototransistor in the above circuit can be modelled as a variable resistor (R_{ph}) between ~5kΩ (light)-1MΩ(dark). We can, again, use Equation 3 to write down the KVL equation for this circuit:

$$I_c + I_{OSC} + I_{ph} = I_{220\Omega} \rightarrow \; C\frac{dV_c}{dt} + \frac{V_c}{R_{OSC}} + \frac{V_c}{R_{ph}} = \frac{V_{cc} - V_c}{220\Omega}$$

$$\rightarrow \frac{dV_c}{dt} + V_c\left(\frac{1}{C}\left(\frac{1}{R_{ph}} + \frac{1}{220\Omega} + \frac{1}{R_{OSC}}\right)\right) = \frac{V_{cc}}{C \cdot 220\Omega}$$

This is, again, a linear differential equation of order 1. We can solve the equation using integrating factor method (again, K is a constant determined by the initial condition on the capacitor).

$$V_c e^{\int \quad Pdt} = \int \quad \left(Qe^{\int \quad Pdt}\right) dt +$$

In which:

$$P = \frac{1}{C}\left(\frac{1}{R_{ph}} + \frac{1}{220\Omega} + \frac{1}{R_{OSC}}\right) = \frac{1}{C}\left(\frac{1}{R_{ph}//220\Omega//R_{OSC}}\right), Q = \frac{V_{cc}}{C \cdot 220\Omega}$$

Plugging in P and Q:

$$V_c e^{\int \quad \frac{1}{C}\left(\frac{1}{R_{ph}//220\Omega//R_{OSC}}\right)dt} = \int \quad (\frac{V_{cc}}{C \cdot 220\Omega}\, e^{\int \quad \frac{1}{C}\left(\frac{1}{R_{ph}//220\Omega//R_{OSC}}\right)dt})dt + K$$

Doing the integrations:

$$V_c e^{\frac{t}{C(R_{ph}//220\Omega//R_{OSC})}} = \int \left(\frac{V_{cc}}{C \cdot 220\Omega} e^{\frac{t}{C(R_{ph}//220\Omega//R_{OSC})}}\right) dt + K$$

$$= \frac{V_{cc}}{C \cdot 220\Omega} \times C(R_{ph}//220\Omega//R_{OSC}) \times e^{\frac{t}{C(R_{ph}//220\Omega//R_{OSC})}} + K$$

$$= V_{cc} \frac{R_{ph}//220\Omega//R_{OSC}}{220\Omega} \times e^{\frac{t}{C(R_{ph}//220\Omega//R_{OSC})}} + K$$

Finally we can divide both sides of the equations by the exponential factor:

$$V_c(t) = V_{cc} \frac{R_{ph}//220\Omega//R_{OSC}}{220\Omega} + K e^{-\frac{t}{C(R_{ph}//220\Omega//R_{OSC})}} \quad \text{(Equation 8)}$$

In which the "//" symbol represents the parallel connection operation:

$$R_1//R_2//R_3 = \frac{1}{\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)} \quad \text{(Equation 9)}$$

Remember in Lab 1 we confirmed that **<u>the smaller resistance dominates in parallel connections.</u>** We know that the oscilloscope will load the circuit with a big resistance (~1MΩ), which is much bigger than the 220Ω resistor. And we know that even the lower bound of the phototransistor voltage (~5KΩ) is much bigger than the 220Ω resistor. Therefore we can safely assume:

$$R_{ph}//220\Omega//R_{OSC} \approx 220\Omega \text{ and } \frac{R_{ph}//220\Omega//R_{OSC}}{220\Omega} \approx 1$$

Equation 6 becomes:

$$V_c(t) \approx V_{cc} + K e^{-\frac{t}{C(220\Omega)}} \quad \text{(Equation 10)}$$

If $V_c(0)$=0, plugging in this initial condition we get:

$$V_c(0) \approx V_{cc} + K = 0 \rightarrow K = -V_{cc}$$

Therefore if we assume $V_c(0)$=0, then Equation 8 becomes:

$$V_c(t) \approx V_{cc} - V_{cc} e^{-\frac{t}{C(220\Omega)}} \quad \text{(Equation 11)}$$

From Equation 10/11 we can see that if we take $t \rightarrow \infty$, $V_c(t \rightarrow \infty) = V_{cc}$. This shows the function of this stage 1 circuit: **<u>The stage 1 circuit forces the voltage across the capacitor to be around Vcc=3.3V,</u>** which gives a set starting voltage (capacitor is always fully charged) for the stage 2 circuit.

The equivalent circuit of the second stage is shown in Figure 14 below:

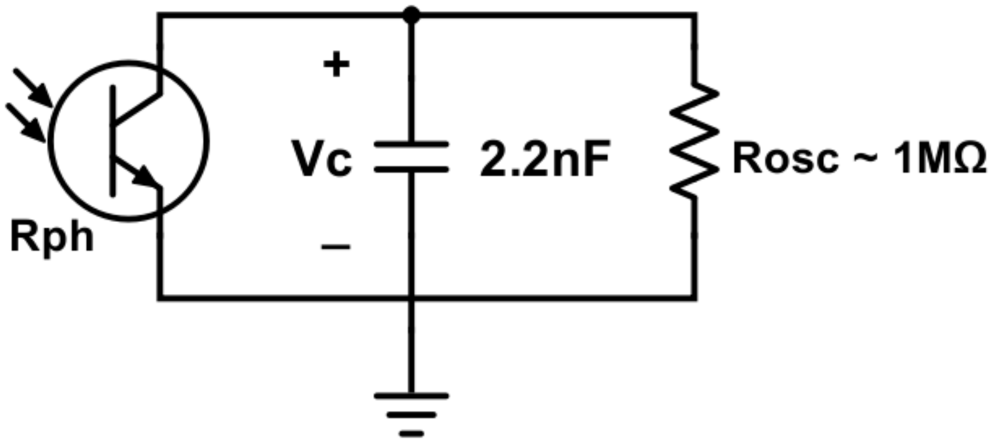


FIGURE 3-14: Simulation of phototransistor circuit in our class project, stage 2

Following similar analysis above we have (Note that we have $V_c(0) = V_{cc}$ for stage 2 thanks to stage 1):

$$V_c(t) = V_{cc}e^{-\frac{t}{C(R_{ph}//R_{OSC})}} \approx V_{cc}e^{-\frac{t}{C \cdot R_{ph}}} \quad \text{(Equation 12)}$$

From Equation 10 we can see that if we take $t \to \infty$, $V_c(t \to \infty) = 0$. The initially fully charged capacitor will be completely discharged in the stage 2 process, if given enough time (>5*R_{ph}C). Note that R_{ph} is around kΩ-MΩ range. So the R_{ph}C value for stage 2 circuit will be much longer than the measurement time in stage 1. You should expect a value in the order of magnitude around hundreds of microseconds (complete "light" condition) to milliseconds (complete "dark" condition).

We know that the effective phototransistor resistance (R_{ph}) changes according to the light intensity on the phototransistor, and the capacitance in the above two circuits is a constant capacitance. Therefore, we can use the RC time constants, or related measurement times, as good figure of merits in telling us quantitatively how "bright" or "dark" the lighting condition/color on top of the phototransistors. In the experiments below you'll be seeing how measurement time measurements can reflect the light intensity conditions on the phototransistors.

Related Phototransistor Circuit Experiment – Experimental Procedures

You will be using a bread board, the AD2 voltage source and oscilloscope, a switch, a 220Ω resistor, a 2.2nF (1nF = 10^{-9}F) capacitor, and a visible light phototransistor to measure the different "measurement times" of the provided phototransistor under three different lighting conditions. We will utilize the oscilloscope to capture the RC circuits' exponential decaying behavior using the oscilloscope's single capture mode and triggering function.

We define the "measurement time" of a lighting condition as the time it takes for the capacitor/phototransistor voltage to drop from ~3.3V (fully charged) to 1V in the experiments below.

You will use this "measurement time" concept when working with the line-following car. To explain, the car uses 8 phototransistors to navigate a black line on white paper. Since each phototransistor has a corresponding LED to illuminate the space below the car, this experiment closely mimics what the phototransistors will "see" in operation on the car. In this way, a "bright" lighting condition is a phototransistor over white paper, a medium "bright" condition is a phototransistor over the gradient between a black line and white paper, and a "dark" condition is a phototransistor over a black line.

Experimental Procedure:

Step 1: Construct the circuit as shown in Figure 3-12. Arrange the IR LED and the IR phototransistor so that they are <u>next to each other and pointing at the ceiling</u>.

You'll be using an on-off SPST (Single Pole Single Throw) toggle switch for this circuit.

<u>Notes on the operation of the switch</u>: looking at the switch will not tell you whether the switch is open or closed. No matter. Build the circuit, excluding the switch but including the oscilloscope, and turn the oscilloscope on. As soon as you connect the switch to the circuit, the capacitor will charge up or not. If it charged up, then the switch is closed ("on" state). Move the switch actuator arm to the other position (the switch will open to the "off" state).

<u>Leave the switch in its off-state when you connect your circuits.</u>

Step 2: Open the AD2 voltage supply and oscilloscope. Change the voltage supply to 3.3 V and adjust your oscilloscope to display a 3.3 V signal. Connect the switch, following the instruction in the note above. You should see a flat line (your signal) roughly sitting on top of the reference line (0V) on your oscilloscope screen. Similar to what you've done in Lab 2, adjust the trigger level to approximately half the 3.3 V supply voltage.

Step 3: Change the Condition in the trigger settings to Either mode (either the rising edge or the falling edge will trigger the measurement on the oscilloscope) and change the trigger type to Normal. Then click Run in the upper left corner of the oscilloscope panel. Once in Run mode, top left of the oscilloscope screen should say Armed. The scope will trigger a sweep when the input voltage crosses the 1.6V level.

FIGURE 3-16: Adjusting the trigger edge type and the acquisition mode

Step 4: Change the time base of your oscilloscope to 100 µs/division. **<u>Flip the switch to its "on" state.</u>** (Now you are charging up the capacitor.) Now you should see near-instantaneous voltage change from 0 V to 3.3 V (Figure 3-17). NOTE: the switch may exhibit *contact bounce*, which will be evident on the oscilloscope (something else that a DMM will not display). This is natural and, in this case, harmless. Contact bounce can be a real problem. One can find numerous contact debouncing circuits online.

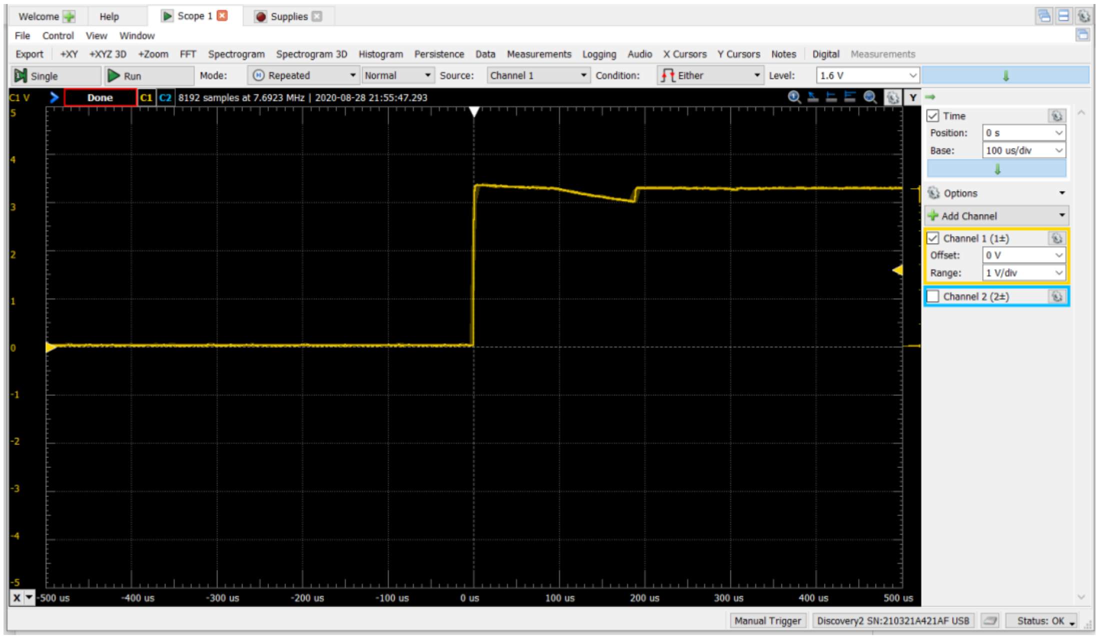


Figure 3-17: Capacitor charging curve (very short charging time)

Step 5: (First lighting condition: complete "bright" condition) Make sure that your phototransistor and LED are covered by your hand. REMEMBER: in this experiment, the LED and phototransistor are both IR devices. As such, the IR rays from the LED will bounce off your hand and are detected by the phototransistor resulting in the bright condition. The RSLK project car works in a similar manner.

Step 6: (Key step) **Flip the switch to its "off" state**. This operation changes your circuit from the circuit in stage 1 to the circuit in stage 2. Now you should see an exponential decay curve on your oscilloscope screen.

Step 7: Firstly, create a Y1 cursor by clicking the "Y" icon in the top right of the oscilloscope view. In the cursor's dropdown menu on the far right, select to place this cursor at 1 V. Now double click the oscilloscope view to being up the X1 cursor. Click the edge of the higher level plateau of the curve (where the signal just starts to decay). Then click on the intersection between the curve and the Y1 cursor to place the X2 cursor. Read the time difference between the X1 and X2 cursors as the measurement time for this condition. NOTE: This measurement time (from 3.3 v to 1 V) is the time used by the RSLK project car. You will be using this time in the project – do NOT forget this point!

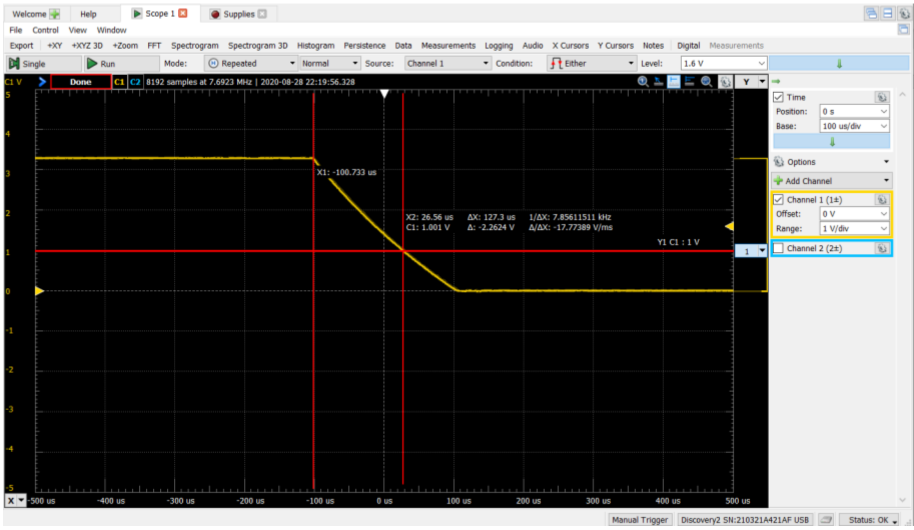


FIGURE 3-18: “High bright” condition discharge curve – measure the measurment time

Step 8: (SKIP THE MEDIUM BRIGHT CONDITION) ~~Second lighting condition: medium “bright” condition)~~ ~~**Flip the switch back to its “on” state**~~~~. Hover your hand about 10cm away vertically from the phototransistor to make sure that you are partially covering the ambient light from your phototransistor.~~

Step 9: (SKIP THE MEDIUM BRIGHT CONDITION) ~~Follow Step 6-8 again for this medium “bright” condition. Again, use the X and Y cursors to help you read the measurement time for this lighting condition. You may need to try different hand position settings to get a discharge time midway between the “dark” and “bright” conditions.~~

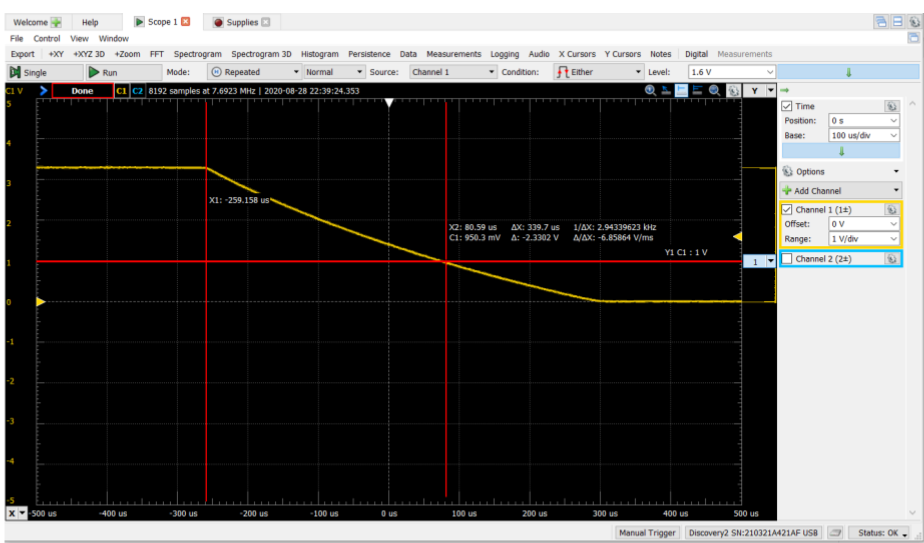


FIGURE 3-19: “Medium bright” condition discharge curve – measure the measurement time

Step 10: (Now the “dark condition”) **<u>Flip the switch back to its “on” state</u>**. Now, hit the “Single button” on your oscilloscope panel again to reset the oscilloscope. Make sure that nothing is covering the phototransistor so that the IR rays do not have anything to bounce off of. Change the horizontal resolution of your oscilloscope to 1**ms/div.**

Step 11: Follow Step 6-7 again for this “dark” condition. Readjust the horizontal resolution to present the discharge curve across a significant portion of the scope screen. Again, use the X and Y cursors to help you read <u>the measurement time</u> for this lighting condition.

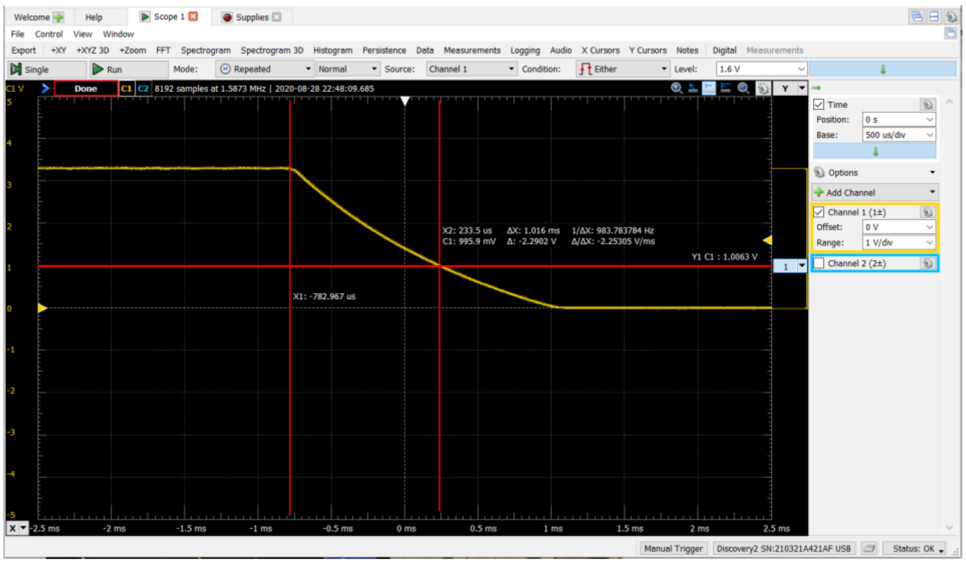


FIGURE 3-20: “Dark” condition experimental curve – measure the measurement time

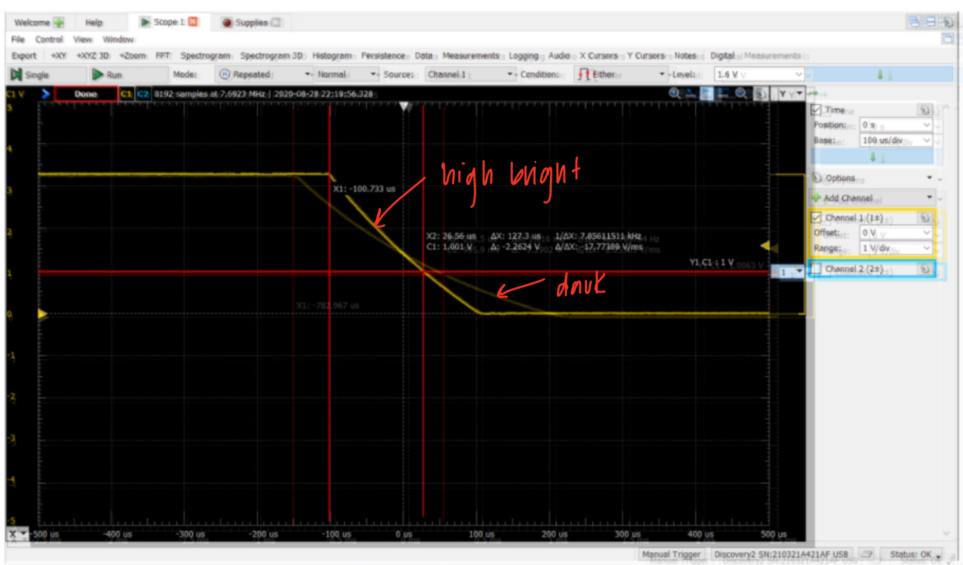
(1) Calculate and tabulate your experimental results in the chart below:

WORK SHEET HERE:			
Condition	Start Time	Measurement Time	Phototransistor Resistance[9]
High Bright	XXXX	1117.397 us	201.96 Ω
Medium Bright	XXXX	XXXX	XXXX
Dark	XXXX	635.001 us	190.37 Ω

(2) Use any plotting software/programming language (e.g., C++, Excel, Matlab, Python…) of your choice, plot the two experimental curves on the same plot (we give **NO** credit for hand-drawn curves). [7]

Please include your plot (screen shot is also ok) on the following page.

Week 3 Lab End



[7] See note below. See also Equation 12, above.