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Overview of the Experiments

In today's lab we will be learning the basic operation principles of light-emitting diodes (LEDs), phototransistors and DC gear motors, which serves as important building blocks for the line-following robot project later on in the course. 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:

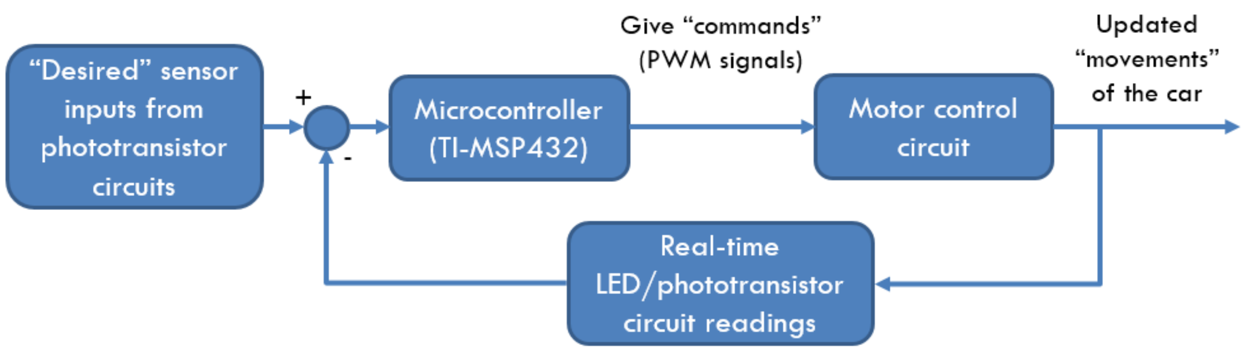


FIGURE 3-1: High level understanding of the ECE3 class project

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. 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 settling times)**, and how we could **control the rotational speed of the motors on the cars with pulse-width modulation (PWM) signals**.

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)

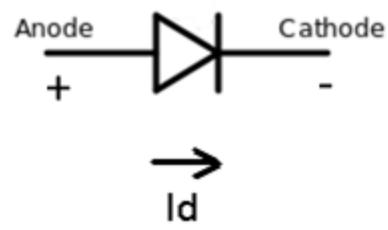


FIGURE 3-2: Diode Symbol

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:

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

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, $V \leq -V_t$:

$$I_d \approx -I_0$$

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. $V \geq V_t$:

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

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.

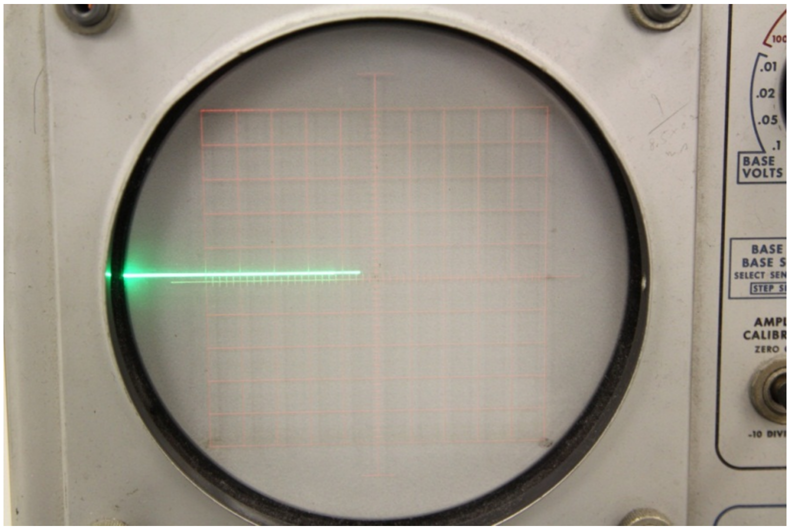


FIGURE 3-3: Diode Reverse Bias Characteristic

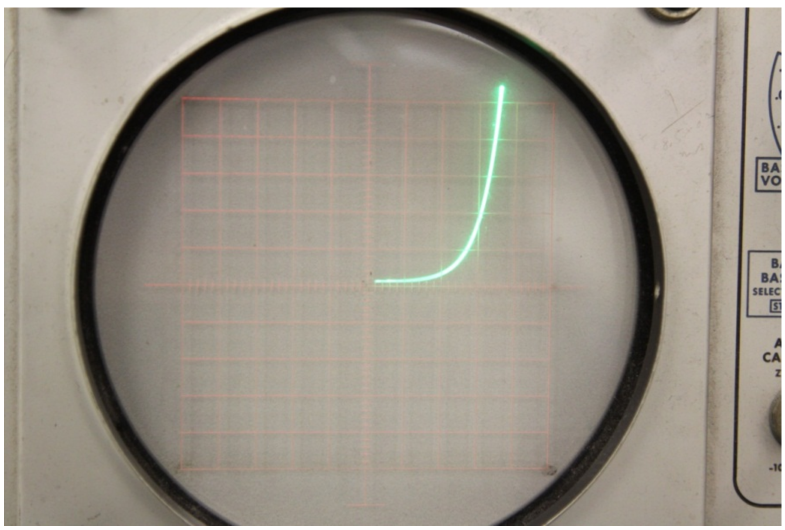


FIGURE 3-4: Diode Forward Bias Characteristic

Note that the power dissipation can be large under reverse bias because the voltage across the device can be quite large (tens of volts) even though the current is small. 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.

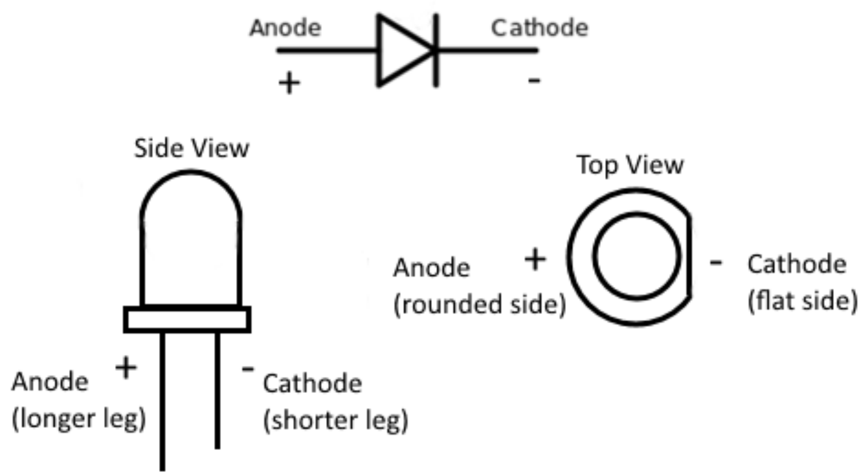


FIGURE 3-5: Physical Diode (VISIBLE LIGHT **ONLY**!)

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** LED which can typically stand up to 20 milliamperes. Set up the circuit as below. **We will not reverse bias the LED, as this may break it!**

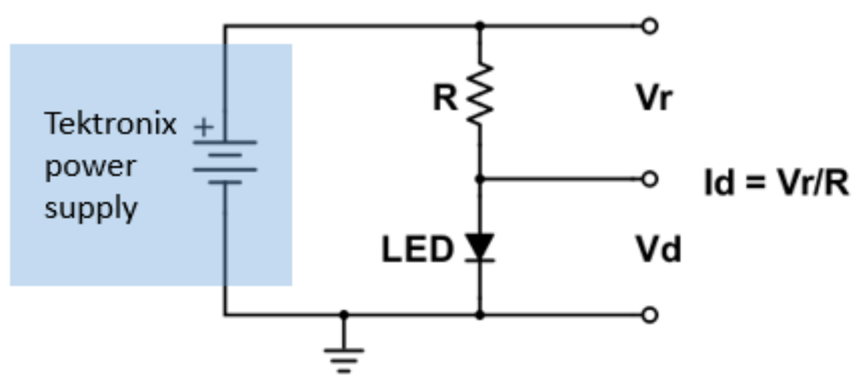


FIGURE 3-6: LED Experiment Setup

The 0-20 volts Tektronix power supply should be connected to the LED under test through a 1000 ohm resistor. Thereby, only a maximum of 20 volt/1K-ohm, i.e. 20 milliamperes can flow.

Using a DMM, measure the voltage across the resistor and the voltage across the LED at given power supply voltages. This allows the measurement of the current through the resistor via Ohm's Law. (Note: the potential across the 1K-ohm resistor = 1000 * I_{device}.) Because this is a series circuit, the current through the resistor is the same as that through the LED.

The setup is shown in the Figures 3-7 and 3-8 below:

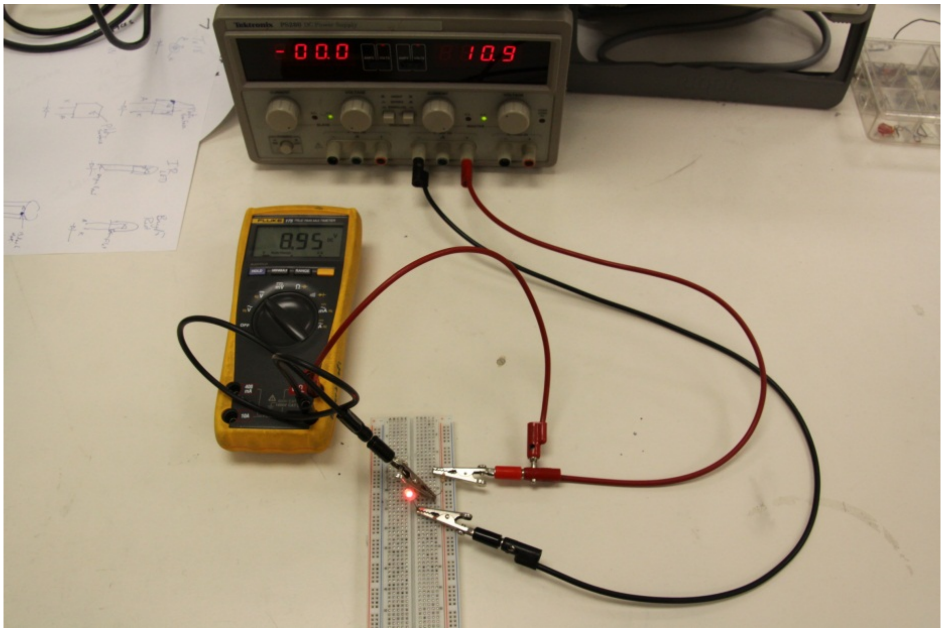


FIGURE 3-7: I VS. V MEASUREMENT SET-UP

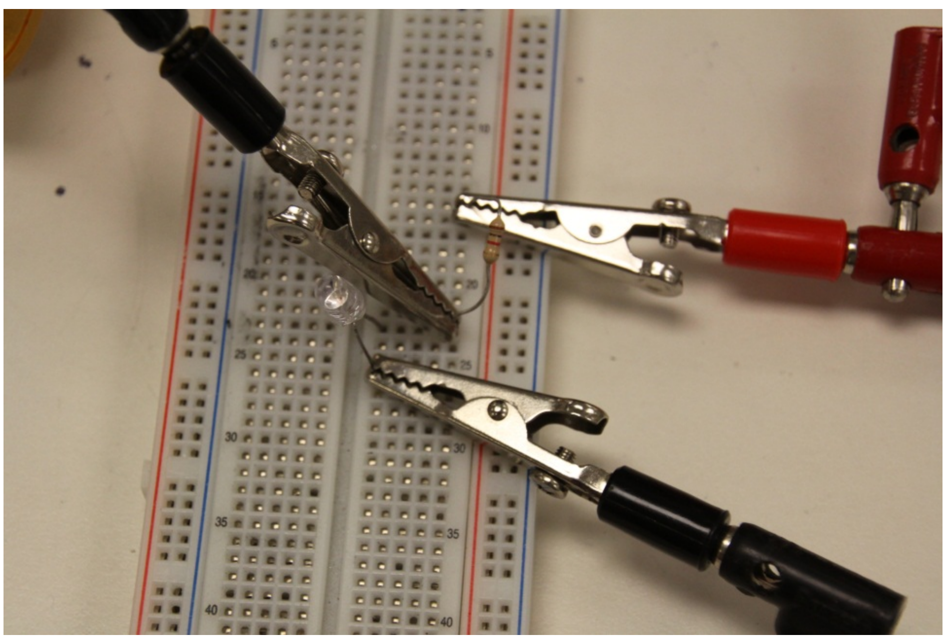


FIGURE 3-8: CLOSE-UP SHOWING LED AND SERIES RESISTOR

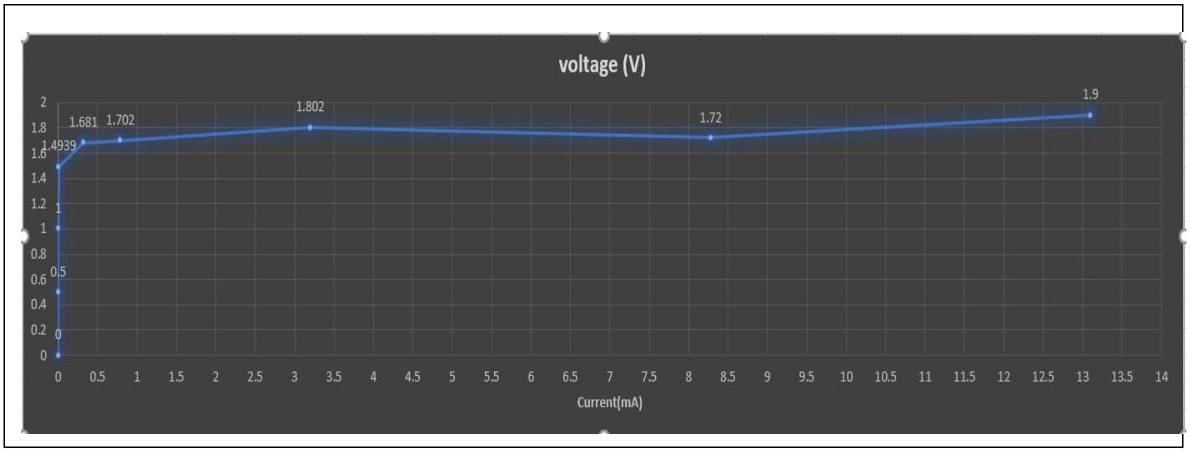
WORK SHEET HERE:

Supply Voltage	Voltage$_{Resistor}$	Voltage$_{LED}$	Current$_{LED}$ ($V_{resistor}$ / 1000)
0 V	0.0 V	0.0 V	0.0 A
0.5 V	0.0 V	0.5 V	0.0 A
1.0 V	0.0 V	1.0 V	0.0 A
1.5 V	0.0061 V	1.4939 V	0.0000061 A
LED on ← 2.0 V	0.319 V	1.681 V	0.000319 A
2.5 V	0.798 V	1.702 V	0.000798 A
5.0 V	3.198 V	1.802 V	0.003198 A
10 V	8.28 V	1.72 V	0.00828 A
15 V	13.1 V	1.9 V	0.0131 A

At approximately what LED voltage does the LED start to glow? 1.681 V

Plot LED current vs. LED voltage in the given space below.

ANSWER HERE



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.)

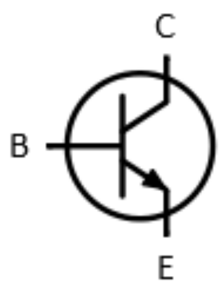


FIGURE 3-9: NPN BJT Symbol

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 settling 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/Dis-charging 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 Equation 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:

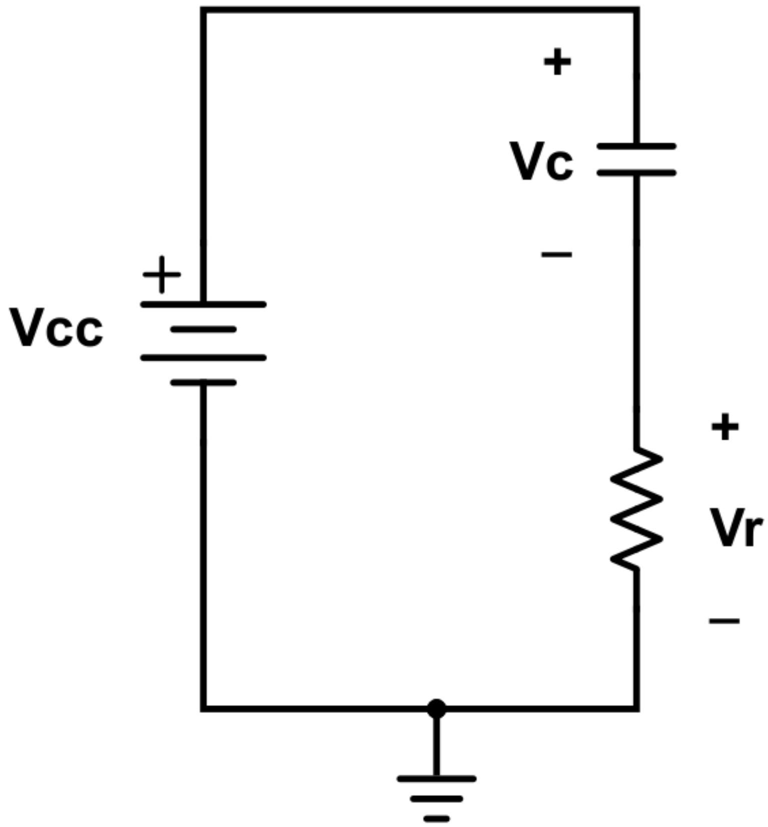


FIGURE 3-10: First Order Series Connection RC Circuit

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:

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

Which simplifies to:

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

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

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:

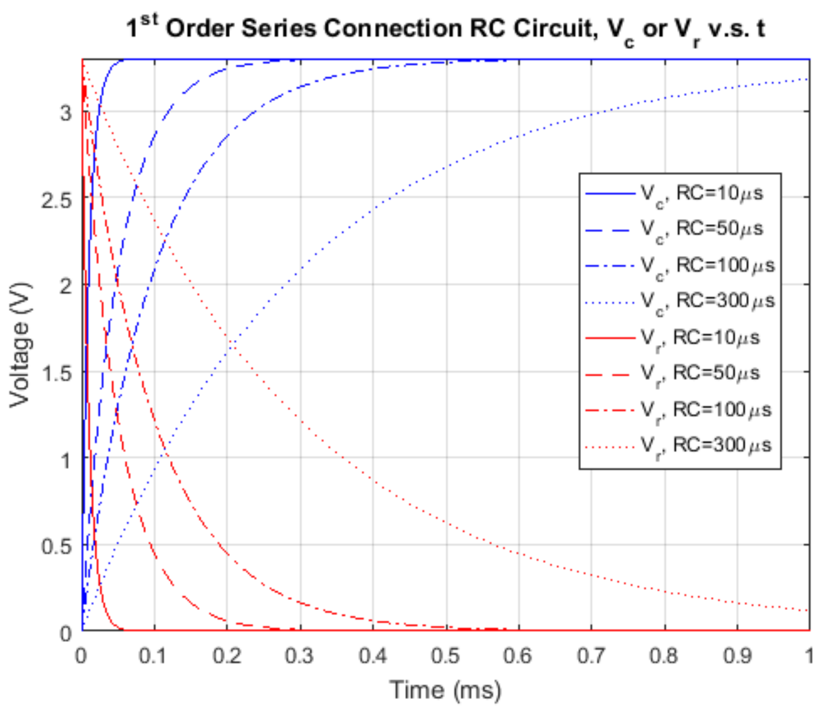


FIGURE 3-11: Voltage across capacitor/resistor over time with different RC time constants

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.

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:

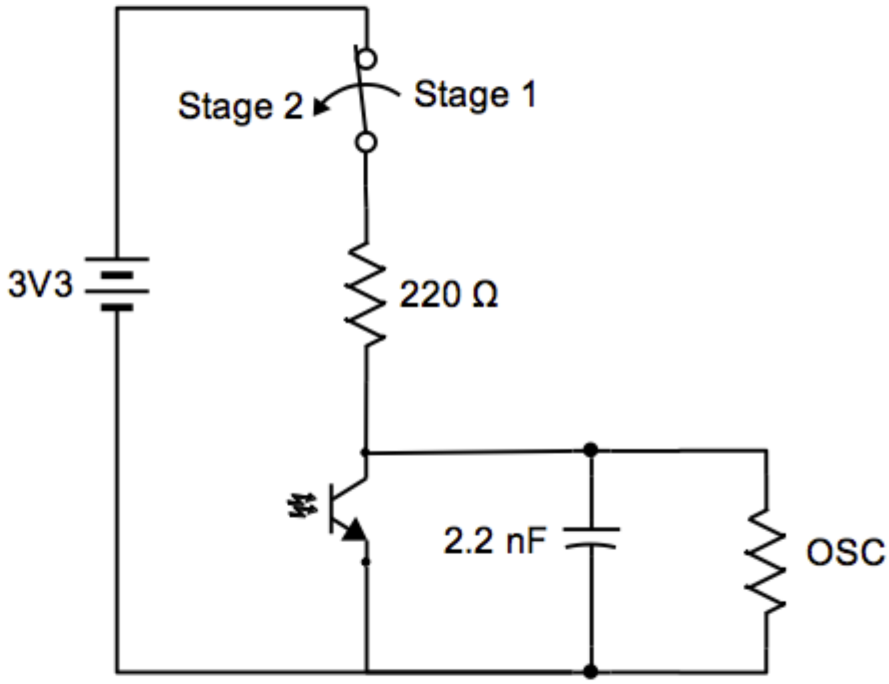


FIGURE 3-12: Phototransistor circuit (stage 1 and stage 2)

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:

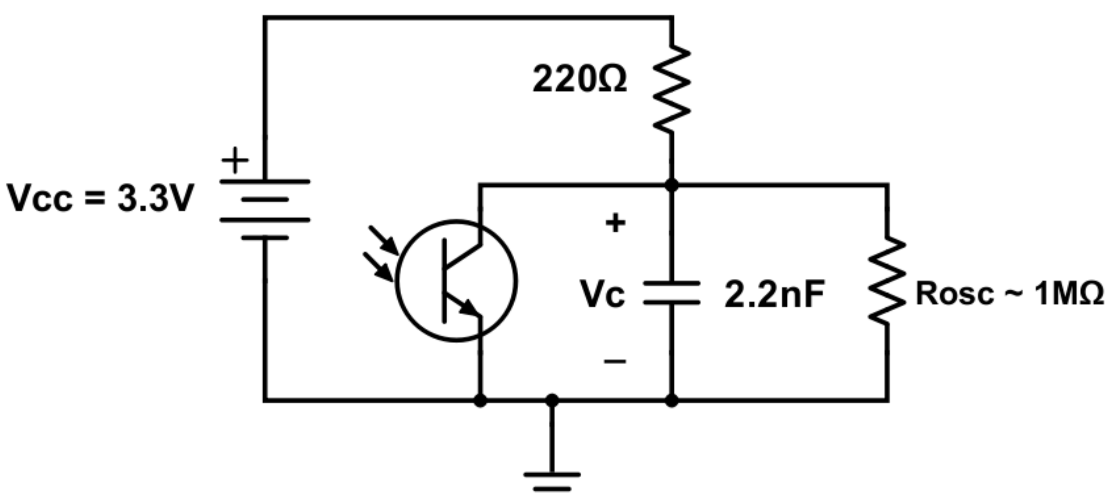


FIGURE 3-13: Phototransistor circuit in our class project, stage 1

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).

$$V_c e^{\int P dt} = \int \left(Q e^{\int P dt}\right) dt + K$$

In which:

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

Plugging in P and Q:

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

Doing the integrations:

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

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

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

Finally we can dived both side of the equations by the exponential factor:

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

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 **the smaller resistance dominates in parallel connections.** 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:

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

Equation 6 becomes:

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

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:

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

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: **The stage 1 circuit forces the voltage across the capacitor to be around Vcc=3.3V,** 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:

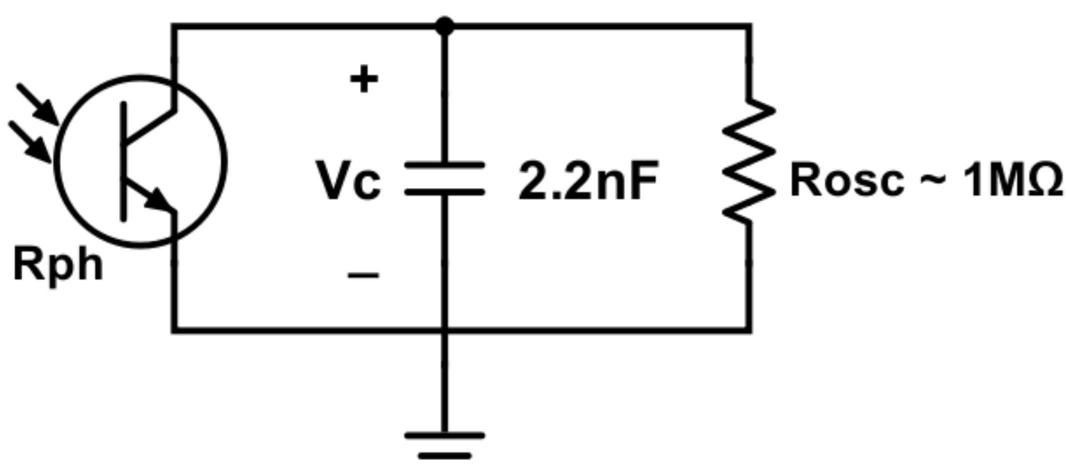


FIGURE 3-14: Phototransistor circuit in our class project, stage 2

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 settling 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 settling 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 settling time measurements can reflect the light intensity conditions on the phototransistors.

Related Phototransistor Circuit Experiment – Experimental Procedures

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

We define the "settling 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.

We would also want to measure the RC time constant of each experimental curve under different lighting conditions. Our working definition of "measured RC time constant" is 1/5 of the time for the capacitor/phototransistor voltage to drop from ~3.3V (fully charged) to ~0V (reference line) in the experiments.

Step 1: Construct the circuit as shown in Figure 3-12. You'll be using an on-off-on SPDT toggle switch for this circuit. See Figure 15 below for its setup:

FIGURE 3-15: On-off-on switch setup

Notes on the operation of the switch: if you keep the toggle arm in its center position then the switch is in its "off" state (i.e., the center lug is not connected to any of the other lugs, which corresponds to stage 2 scenario). If you switch the arm to the right then the switch is in its "on" state (i.e., the left and the center lugs are connected, which corresponds to stage 1 scenario).

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

Step 2: You should now 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 "Slope" in the "Trigger Menu" to "↕ Either" mode (either the rising edge or the falling edge will trigger the measurement on the oscilloscope). Then push the big button with a label "Single" on the upper right corner of the oscilloscope panel, in order to switch the oscilloscope from the continuous acquisition mode to a single capture mode.

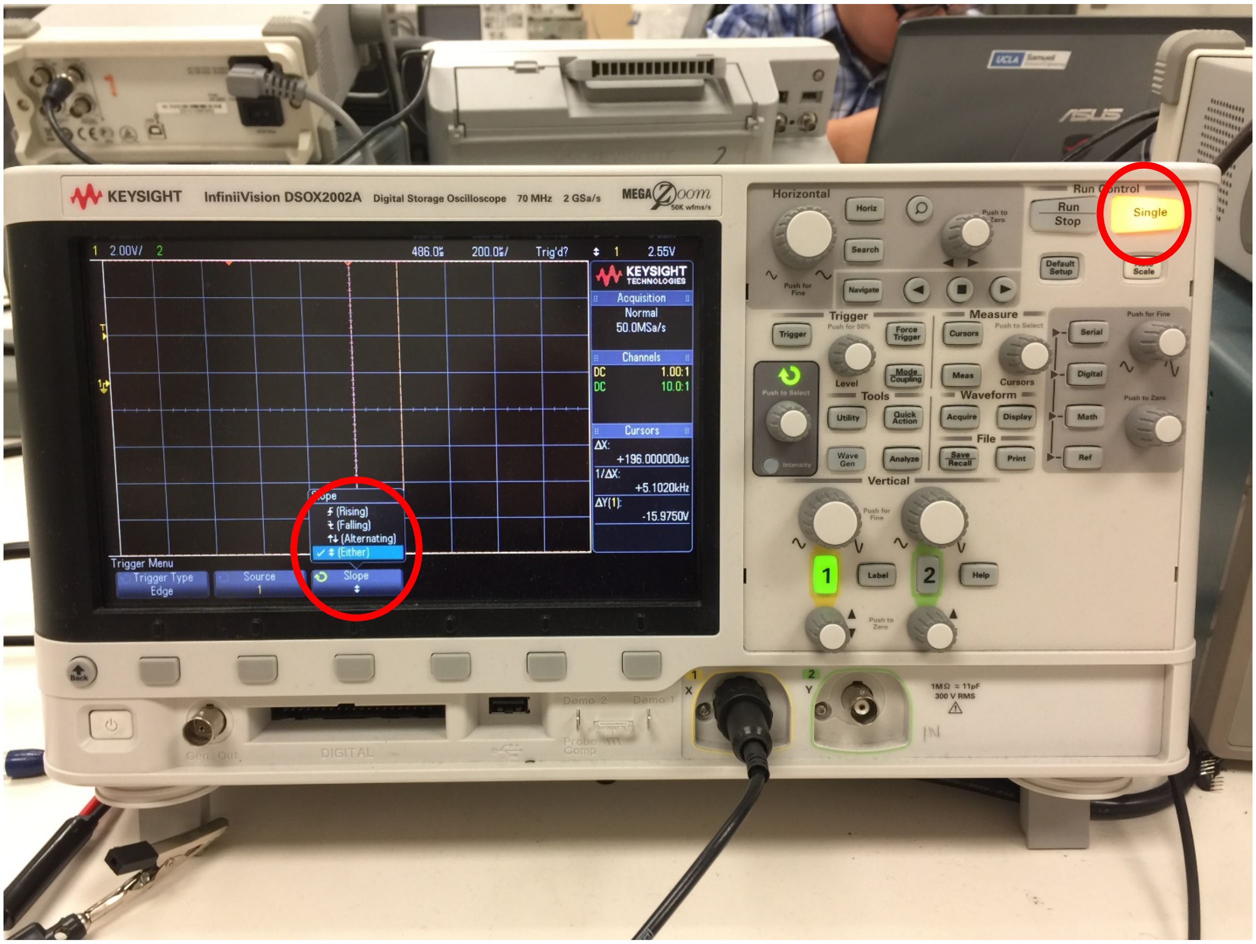


FIGURE 3-16: Adjusting the trigger edge type and the acquisition mode

Step 4: Change the horizontal resolution of your oscilloscope to 100 µs/block. **<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. 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 on line.

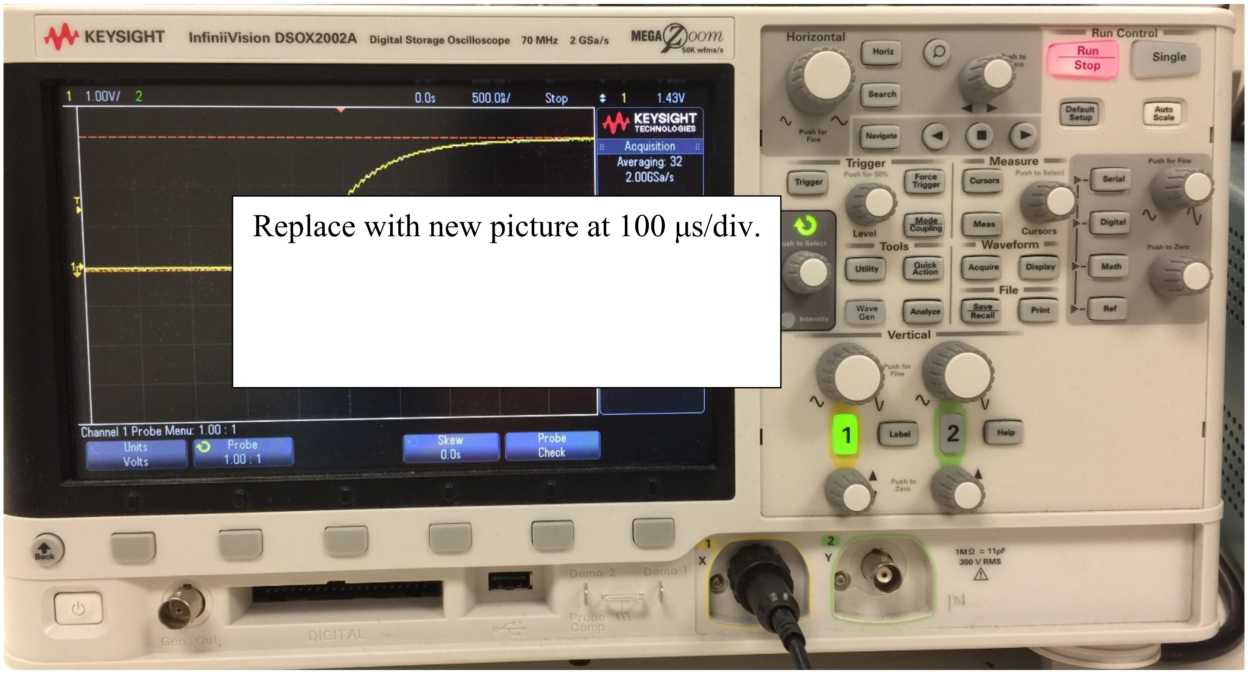


FIGURE 3-17: Capacitor charging curve

Step 5: (First lighting condition: complete “bright” condition) Hit the “Single button” on your oscilloscope panel again to reset the oscilloscope. Make sure that your phototransistor is well exposed to ambient light (nothing covering it).

Step 6: (Key step) <u>**Flip the switch to its “off” state**</u>. 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, align one of the X cursors (X1 cursor) to the edge of the higher level plateau of the curve (where the signal just started to decay). Then you can align the Y cursor to about 1V above the reference line. Finally, you can use the other X cursor (X2 cursor) to align to the same horizontal position as the intersecting point between the signal curve and the Y cursor at 1V level. Read the time difference between the X1 and X2 cursors as the <u>settling time</u> for this condition.

Step 8: Also we would like to measure the RC time constant for this condition. This is done by keeping your X1 cursor at the same position where the signal just start to decay, and move the X2 cursor to the starting point of the lower plateau (which is around the reference line). Read the time difference between the X1 and X2 cursors; divide this value by 5 to get the <u>RC time constant</u> for this condition.

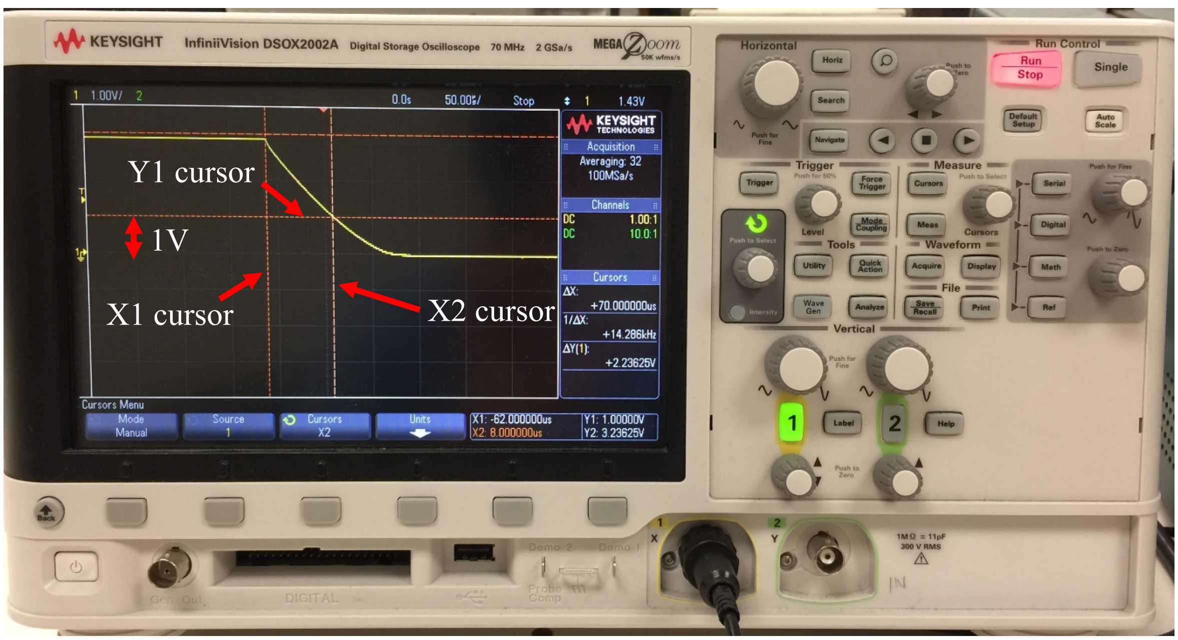


FIGURE 3-19: “Complete bright” condition experimental curve – measure the settling time

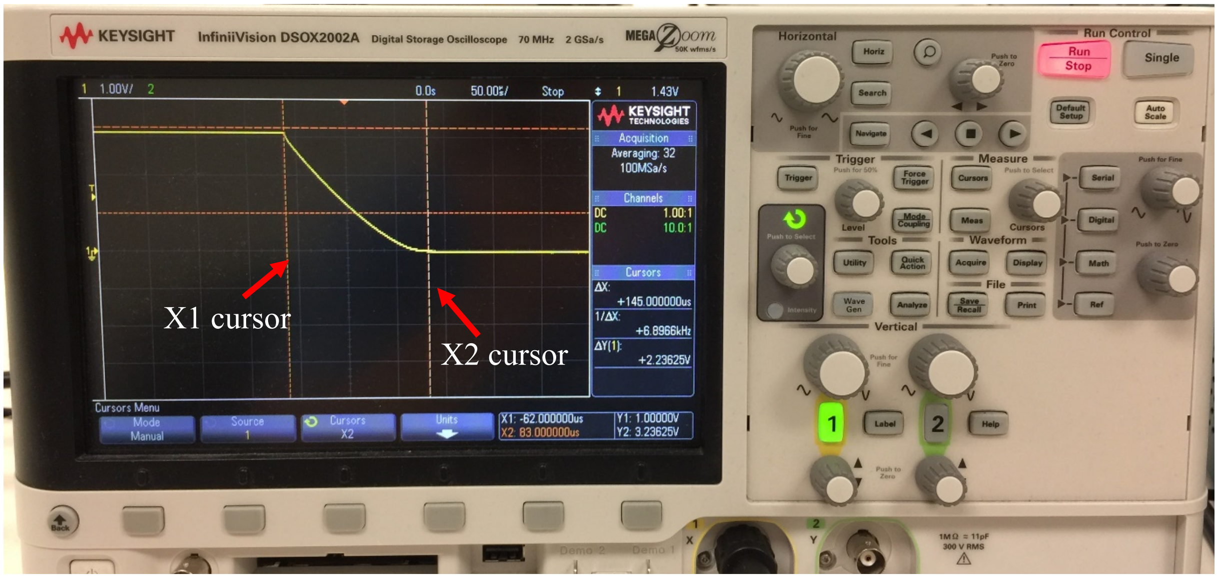


FIGURE 3-20: “Complete bright” condition experimental curve – measure the RC time constant

Step 9: (Second lighting condition: medium “bright” 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. Hover your hand about 10cm away vertically from the phototransistor to make sure that you are partially covering the ambient light from your phototransistor. Change the horizontal resolution of your oscilloscope to 100μs/block.

Step 10: Follow Step 6-8 again for this medium “bright” condition. Again, use the X and Y cursors to help you read <u>the settling time</u> and <u>the RC time constant</u> for this lighting condition.

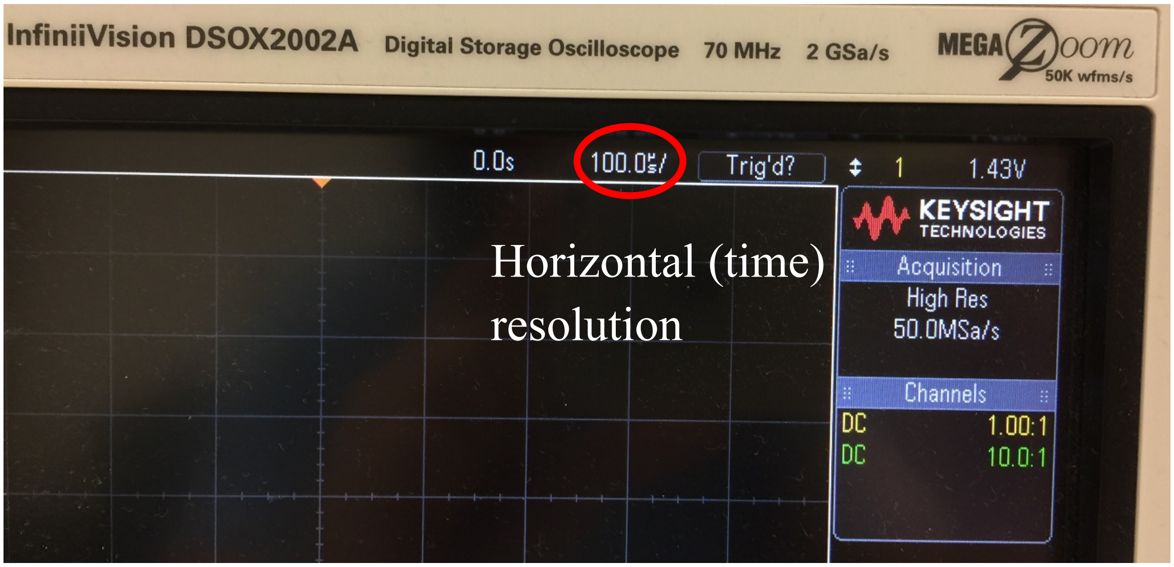


FIGURE 3-21: Adjusting the horizontal (time) resolution again

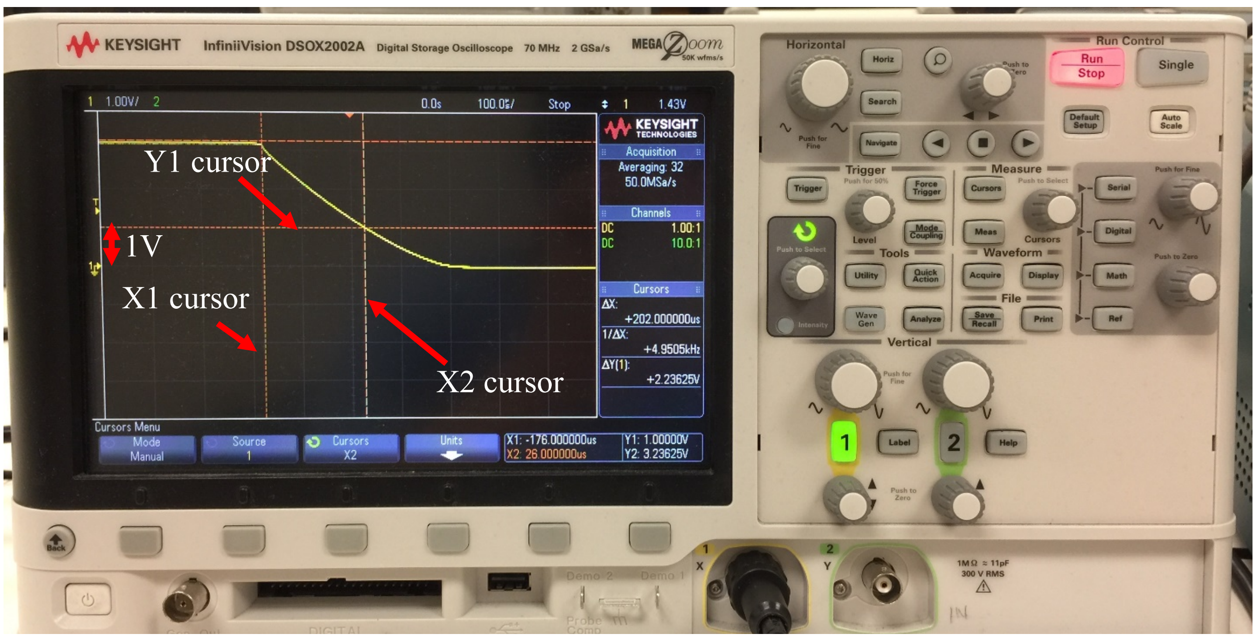


FIGURE 3-22: “Medium bright” condition experimental curve – measure the settling time

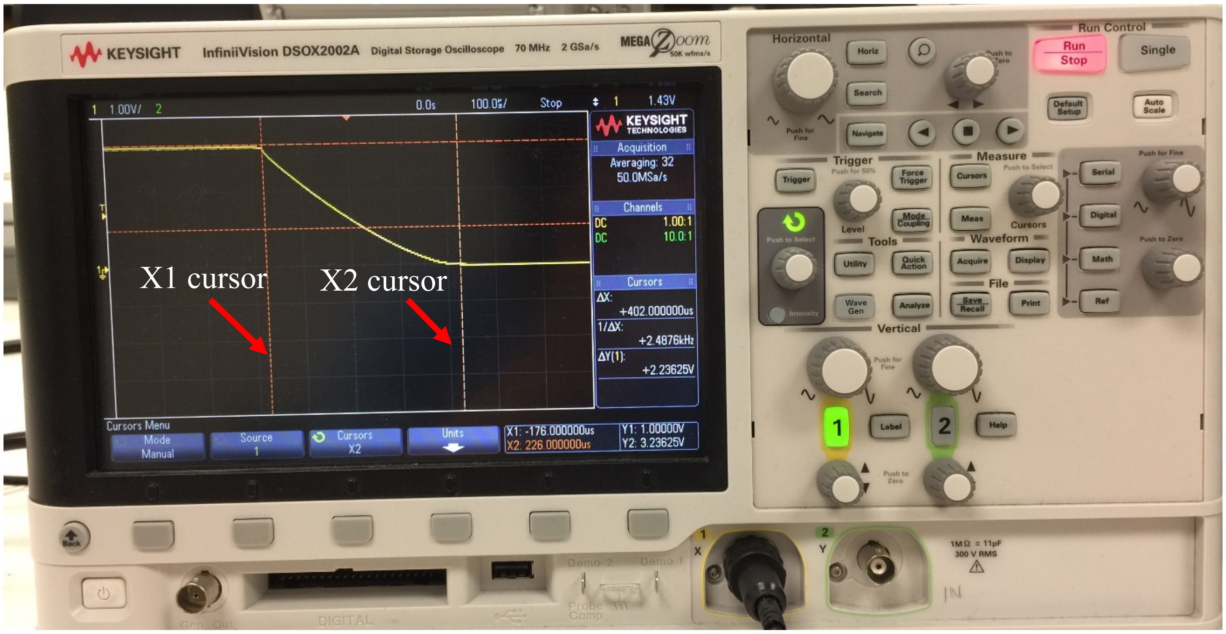


FIGURE 3-23: “Medium bright” condition experimental curve – measure the RC time constant

Step 11: (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. Cover the phototransistor with your hand to make sure that minimal ambient light can shine on your phototransistor. Change the horizontal resolution of your oscilloscope to 500μs/block.

Step 12: Follow Step 6-8 again for this “dark” condition. Again, use the X and Y cursors to help you read <u>the settling time</u> and <u>the RC time constant</u> for this lighting condition.

FIGURE 3-24: Adjusting the horizontal (time) resolution again

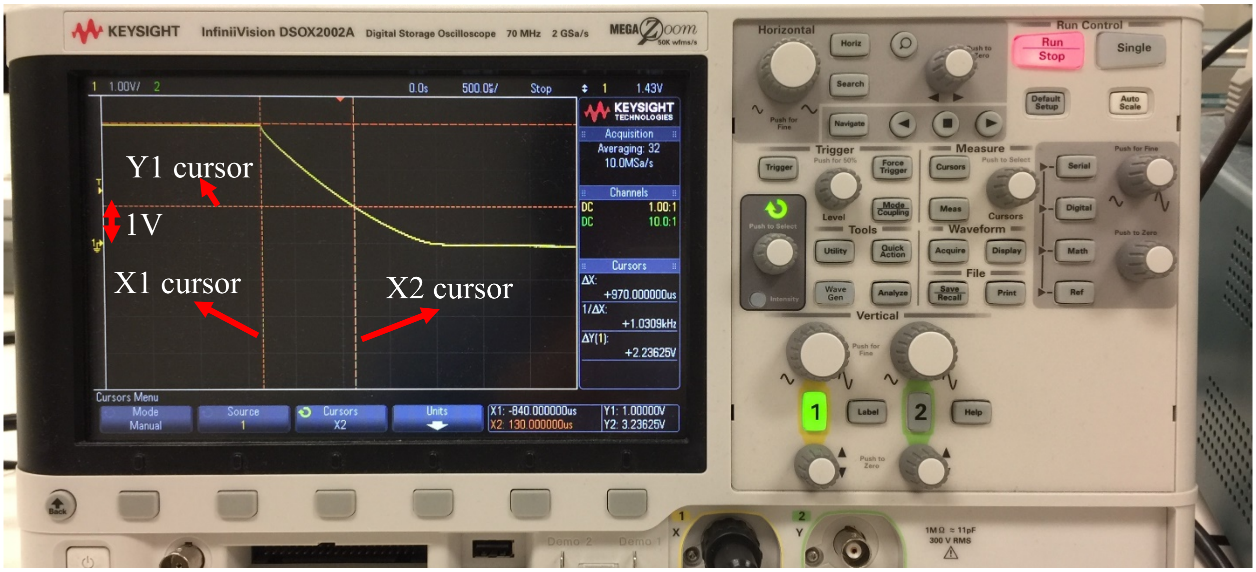


FIGURE 3-25: “Dark” condition experimental curve – measure the settling time

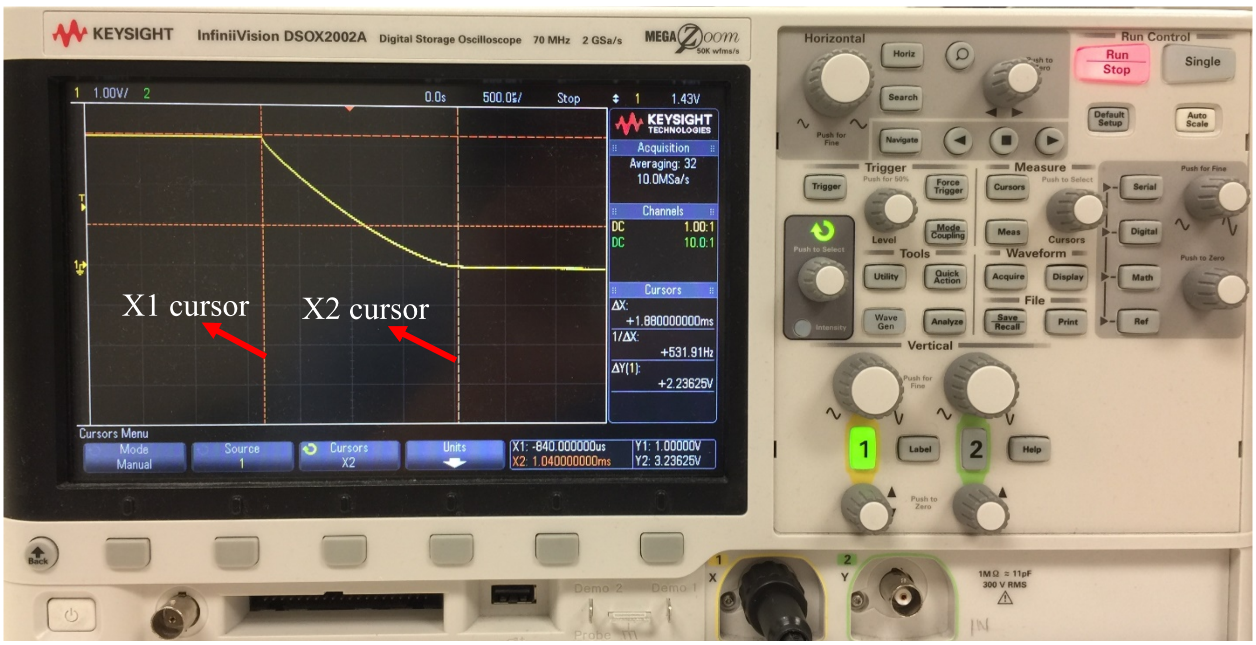


FIGURE 3-26: “Dark” condition experimental curve – measure the RC time constant

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<u>(1) Calculate and tabulate your experimental results in the chart below</u>:

WORK SHEET HERE:

Condition	Settling Time (3.3V to 1V)	RC Time Const.
Complete bright	60.4 µs	50.59 µs
Medium bright	720 µs	603.05 µs
Dark	2.2 ms	1.843 ms

(2) Use any plotting software/programming language (e.g., C++, Excel, Matlab, Python…) of your choice, plot the three experimental curves on the same plot (we give **NO** credit for hand-drawn curves). We can assume that the two experimental (phototransistor voltage vs. time) curves follows Equation 12, and the RC time constants are the three time constants you've measured in the above experiments: (Assume that at t=0 we flipped the switch)

$$V_c(t) = 3.3e^{-\frac{t}{R_{ph}C}}\ volts \iff -\frac{t}{RC} = \ln\frac{V_c}{3.3} \iff RC = \frac{-t}{\ln\frac{V_c}{3.3V}}$$

Please include your plot (screen shot is also ok) below: